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SURFACE WAVE ANALYSIS PACKAGE AND SHAGAN RIVER TO SRO STATION PATH CORRECTIONS

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This report describes the S-CUBED Surface Wave Analysis Package and its application to obtaining surface wave path corrections. The package is applied first to a synthetic seismogram. Using this as an example, a detailed explanation of how to use the codes is given. The codes are then applied to a set of Shagan River explosion seismograms recorded at SRO stations.

ABSTRACT (Continued)

Three large computer codes are included in the Surface Wave Analysis Package. The first, TELVEL, obtains phase and group velocities and spectral amplitudes from a seismogram by using narrow-band filtering and phase-matched filtering. The second, INVERT, inverts the phase and group velocities for earth structure, and then inverts for moment and Q structure, by comparing synthetic and observed spectral amplitudes. The third, SYNSRF, generates synthetic seismograms, dispersion curves and eigenfunctions. These three codes are used together to obtain a Green's function for the source-station travel path.

For each SRO station travel path we obtain phase and group velocities and an average path structure. In addition, the narrow-band filtered seismogram provides an indication of station quality by revealing stations with severe multipathing or other problems. Stations KONO and SHIO prove to be excellent stations with very clean group velocity curves. Stations MAJO, GRFO, ANTO, and CHTO show clear evidence of multipathing, but are still useable. Station KAAO shows severe multipathing resulting in a bifurcated group velocity curve.

This report is intended to provide a users manual for the Surface Wave Analysis Package. The appendices contain file formats, sign conventions, an explanation of some of the algorithms used in the programs, and definitions of output quantities, as well as a detailed description of program TELVEL.

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I. SURFACE WAVE ANALYSIS PACKAGE

This report describes the S-CUBED Surface Wave Analysis Package which is designed to obtain path corrections from observed seismograms. There are three main programs in the package. The first -- TELVEL, uses the method of phase-matched filters (Herrin and Goforth, 1977) to recover surface wave phase and group velocities. The second -- INVERT, inverts the phase and group velocities to obtain the earth structure for the path, and obtains an approximate Q structure and moment by comparing synthetic and observed spectral amplitudes. The third -- SYNSRF, uses a variety of methods (Takeuchi and Saito (1972), Schwab and Knopoff (1970), Harkrider (1964, 1970)) modified for high frequency stability, to synthesize surface waves.

All programs are interactive and self-contained. Every effort has been made to make them as easy to use as possible. In this report we show the uses of the programs for making path corrections by going through an example in detail using a synthetic seismogram, and by applying the method to Shagan River -- SRO station travel paths.

1.1 WHAT IS A PATH CORRECTION?

A path correction is a Green's function for a given source region and source-to-receiver path. Once the Green's function is known, it may be used to generate synthetic surface waves from an arbitrary source, as observed at the receiver point, or the inverse problem may be solved: an observed seismogram may be used to estimate the strength and type of the source, usually in the form of a moment tensor.

The basic procedure used to make a path correction was outlined in an earlier report (Wang, et al., 1981). Since then the procedure has been improved by allowing simultaneous estimation of Q and moment, and by making the codes interactive and compatible.

1.2 HOW TO MAKE A PATH CORRECTION

To make a path correction, simply take a seismogram, use program TELVEL to obtain the Rayleigh wave phase and group velocities, then use program INVERT to find the average source-to-receiver shear velocity and Q structure, and finally use program SYNSRF to generate eigenfunctions for this structure, and to compute a synthetic seismogram which resembles the original seismogram. The scalar moment of the explosion is found together with the estimate of Q, and the eigenfunctions can be used to perform a moment tensor inversion for any source in the same area as the original explosion.

In practice, finding a path correction is more than a routine operation, and there are a number of ways to err during the data processing. The purpose of this section is to go through the procedure in some detail and to identify the traps which are lurking to confuse the user. Fortunately, most of the errors which can be made will show up somewhere during the processing. A bad set of phase and/or group velocities may not produce a reasonable earth model when inverted. An inaccurate inversion for shear velocity may make it impossible to determine a reasonable Q structure. If the seismogram obtained at the end of the procedure is a good match to the original (except for noise or multipathing effects, etc.), then chances are very good that the path correction has been accurately found.

The first step in making a path correction is to collect all of the information pertaining to the seismogram. The following items are required:

1. A seismogram sampled at evenly spaced points in REALIO format (see Appendix 1), preferably demeaned, detrended and tapered
2. The number of points in the seismogram
3. The sampling interval for the seismogram

4. The time delay between the source time and the start of the seismogram

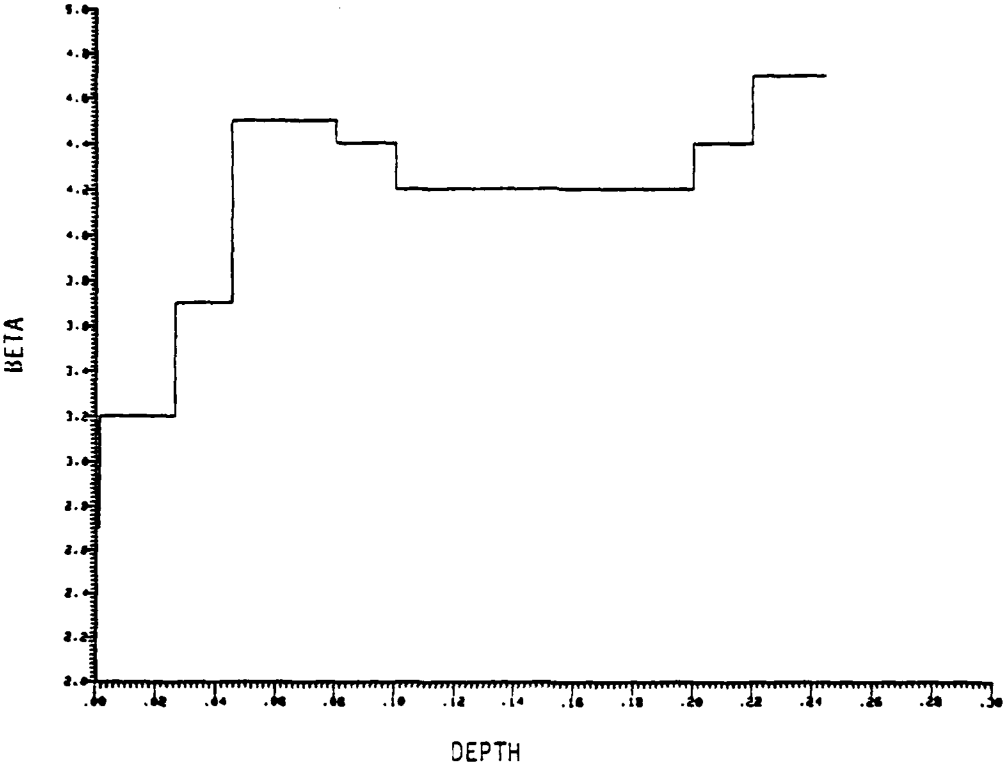
5. The distance from the source to the receiver

6. The instrument response expressed as a ratio of polynomials also in REALIO format

It is very important to have an accurate estimate of source to receiver distance, and the seismogram start time. It is well worth double checking these numbers since everything that follows will be wrong if these numbers are incorrect. Of course, errors of a few seconds or a few kilometers may not result in major errors in the final results, but it is the abundant typos and minute errors that can be disastrous. The best way to be sure of timing is to compare several seismograms for the same path to be sure the times are all consistent.

Several small utility codes are available which allow the conversion of any seismograms to REALIO format as well as detrending, demeaning, etc., and which put instrument responses in the proper format (see Appendix 2). Instrument responses must be known as polynomials; no provision is currently made for tabulated instrument responses. One additional quantity is required by TELVEL -- the initial phase of the source. For an explosion (vertical component, displacement, positive up, Rayleigh wave) the initial phase is $-3\pi/4$. In order to illustrate the procedure we apply the entire surface wave analysis package to a synthetic seismogram. This is a useful exercise to go through before processing data for a new area, as the results help to identify certain problems in advance, and may help to identify the correct 2π branch in the phase velocity analysis. If an approximate structure is available for an area, it should be used to make a similar test.

A synthetic seismogram was constructed (with program SYNSRF) using the structure listed and shown in Figure 1. The synthetic was computed using an SRO long period instrument at a distance of 3000 kilometers and an explosion source with a Ψ_∞ (the long period limit



THICKNESS (m)	ALPHA (m/sec)	BETA (m/sec)	RHO (Kg/m^3)	Q
1100.0	5000.0	2700.0	2100.0	150.0
25000.0	5900.0	3200.0	2500.0	250.0
19000.0	6800.0	3700.0	2800.0	400.0
20000.0	8100.0	4500.0	3300.0	600.0
15000.0	8200.0	4500.0	3300.0	600.0
20000.0	8000.0	4400.0	3300.0	100.0
100000.0	7800.0	4200.0	3200.0	90.0
20000.0	8000.0	4400.0	3300.0	100.0
80000.0	8500.0	4700.0	3500.0	200.0

Figure 1. East Kazakh shear velocity structure used for synthetic seismogram.

of the reduced velocity potential) of one cubic meter. The synthetic seismogram and true phase and group velocity dispersion curves are shown in Figure 2. Figure 3 shows a form summarizing the inputs and outputs to the programs. It is useful to have a similar form available before starting the procedure.

1.2.1 Recovery of Phase and Group Velocities and Spectral Amplitudes

With this information in hand, the next step is to run TELVEL. The first phase of TELVEL is to apply a set of narrow band filters to the seismogram to obtain an approximate set of group velocities. The choice of filter frequencies and filter widths (specified in terms of the filter Q) is up to the user. From experience, a Q of 10 provides a good filter width for most data. For long period data, such as SRO data, 20-40 frequencies from .01 to .1 Hz usually produces a good group velocity curve over the reliable frequency range of data (see Figure 4). Occasionally, the program will encounter difficulties in finding a good group velocity curve. If it does, try going back and using more or fewer frequencies or a lower or higher Q. Sometimes the program will find a good set of group velocities as evidenced by the peaks on the plot, but will not recognize it (no curve will be drawn through them). If so, they can be entered by hand using the edit command. The narrow band filter is an important step in finding the group and phase velocities. Not only does it provide an initial group velocity estimate, but it may show up features such as bifurcated group velocity curves which may render the phase matched filter unstable.

The purpose of TELVEL is to improve the initial estimate of group velocity by phase matched filtering while eliminating interfering multipath arrivals, higher modes and noise, and to find the phase velocities. The phase matched filter is found by integrating the group delay found initially by narrow band filtering. When the filter is applied to the original seismogram, the true surface wave is compressed into a narrow time window. The

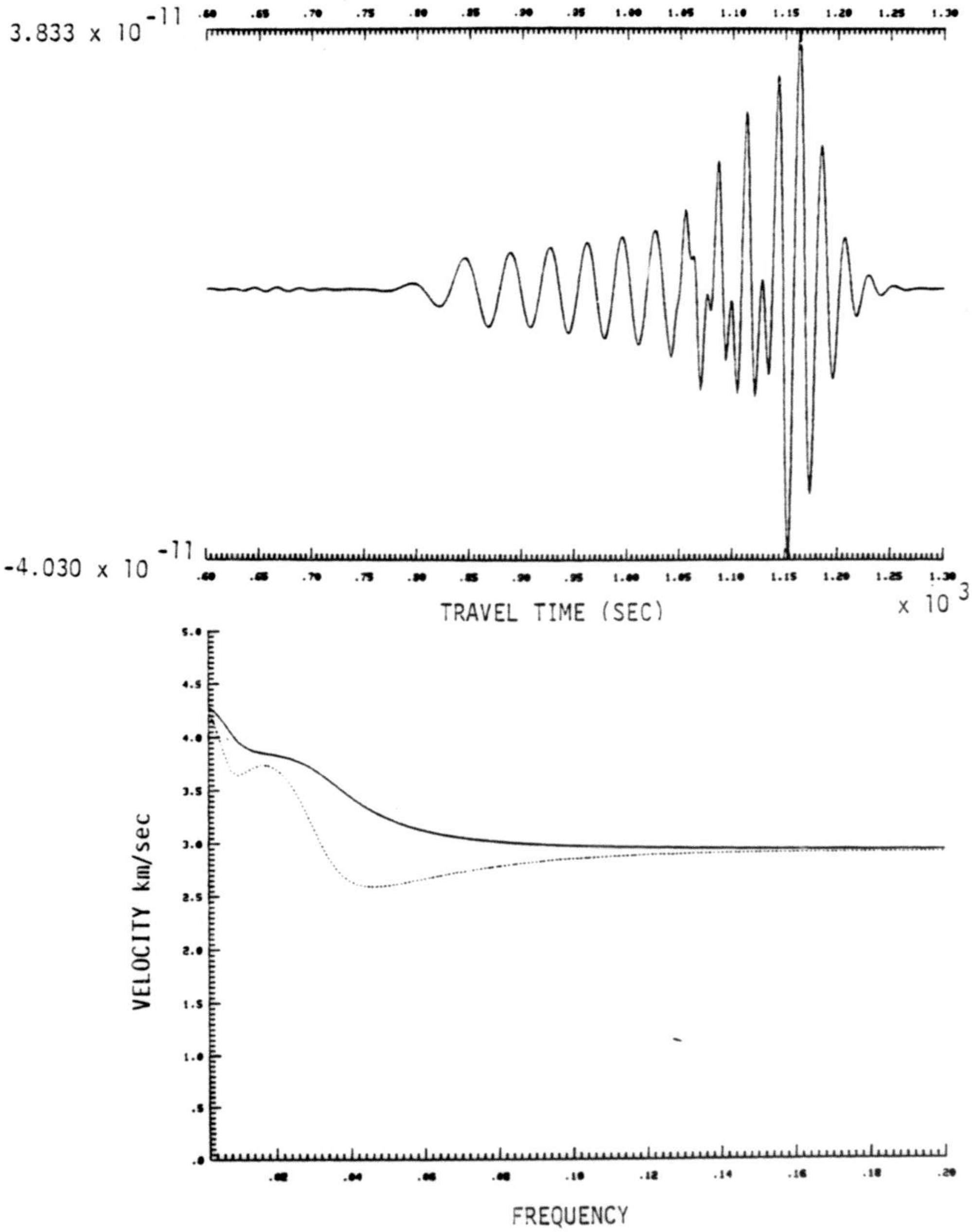


Figure 2. Synthetic seismogram (top) for the fundamental mode Rayleigh wave made using East Kazakh structure (Figure 1) and dispersion curves (bottom). Solid line is phase velocity, dashed is group velocity.

Source Location: East Kazakh

Receiver Location: Synthetic α 3000 km

Source Time: 0 sec

Receiver Time: 600sec

Delay Time: 600 sec

Distance: 3000 km

Seismogram File: RSYN * EKSRO

Number of Points: 901

ΔT: 1.0 sec

Instrument: SRO-LP

Initial Phase = - 0.75

Narrow Band Filters Used

NF, FMIN, FMAX, Q = 30, .01, .1, 10

TELVEL Output File(s): TEL * EKSRO

Eigenfunction File for Source Region EF * EKAZ2

Instrument Gain (conversion to meters) 1.

Estimated Moment = 6.4×10^{11} /Gain = 6.4×10^{11}

Estimated Ψ_∞ = .980 /Gain = .980

INVERT Output File(s): INV * EKSRO

SYNSRF

Frequencies Computed: 100, .002, .2

Output Files: EF * EKSRO

Estimated M_s: 0.04

Comments: Test on Synthetic Seismogram

PATH CORRECTION INFORMATION

Figure 3. Form summarizing inputs and outputs for Surface Wave Analysis Package.

SEC 8. OPTION(H=HELP) ? >1 L
GROUP VELS PICKED:

IDX	FREQ	GRPV	AMPL
1	.0105	3.656	.030
2	.0136	3.698	.069
3	.0168	3.721	.123
4	.0200	3.678	.195
5	.0232	3.564	.282
6	.0263	3.393	.369
7	.0296	3.175	.449
8	.0330	2.942	.544
9	.0364	2.767	.673
10	.0393	2.674	.822
11	.0420	2.631	.944
12	.0445	2.612	1.000
13	.0469	2.607	.985
14	.0493	2.609	.915
15	.0518	2.616	.814
16	.0544	2.627	.703
17	.0570	2.641	.59[illegible]
18	.0599	2.658	.506
19	.0632	2.677	.430
20	.0661	2.695	.368
21	.0690	2.712	.315
22	.0716	2.728	.270
23	.0743	2.743	.231
24	.0771	2.756	.197
25	.0800	2.769	.169
26	.0825	2.780	.145
27	.0850	2.791	.124
28	.0876	2.801	.106
29	.0904	2.809	.091
30	.0933	2.817	.078

SEC 8. OPTION(H=HELP) ? >

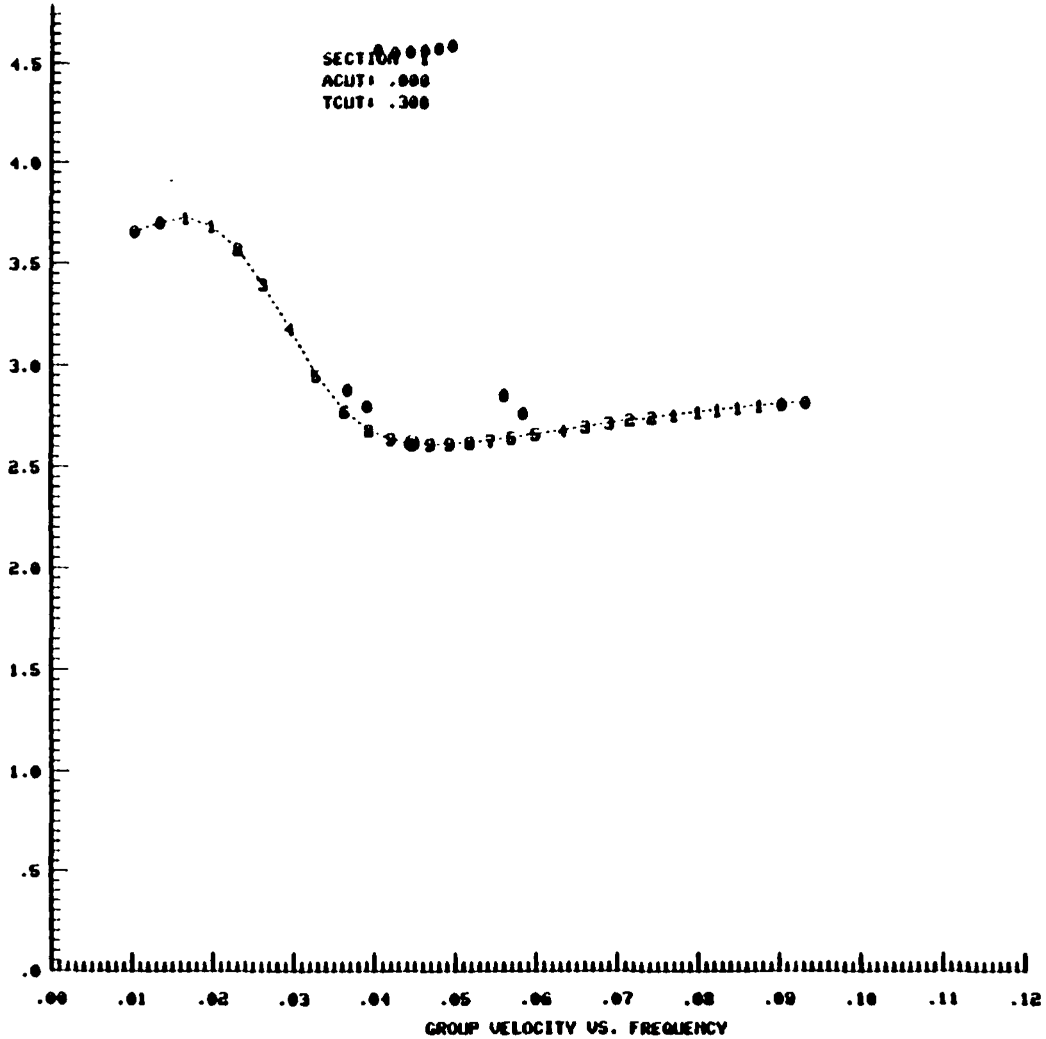


Figure 4. Group velocity curve obtained by narrow band filtering the synthetic seismogram in Figure 2.

resulting phase matched filter output is plotted by TELVEL to allow windowing of the time series (see Figure 5). It is important to choose a time window large enough to contain most of the energy in the main arrival, but small enough to eliminate most of the noise and multiple arrivals from the filter. The best way to choose the time limits is to look at the phase matched filter output and then back up to apply the appropriate time window. For long period data a time window of 50-100 seconds on each side of the main pulse is usually appropriate.

After the phase matched filter is applied to the seismogram, the filter phase is unwrapped and used to estimate the phase velocities of the Rayleigh wave. Since any multiple of 2π may be added to the phase, there is an uncertainty introduced into the phase velocity. If ϕ is the phase of the surface wave (ϕ is always < 0) then the phase velocity is given by

$$C = \frac{-2\pi fr}{\phi - \phi_0 + 2\pi n}$$

where r is the distance, ϕ_0 is the initial phase, f is the frequency and n is an undetermined integer. The choice of the correct value of n is often difficult. In order to help choose the correct value of n, TELVEL plots the phase velocity for a user specified value of n together with values of $n \pm 1$ (see Figure 6). The following facts help in the choice of n.

1. The true phase velocity approaches a constant in the low frequency limit. If the phase velocity is well determined, values of n which are too small cause the phase velocity to decrease rapidly at low frequencies, while values of n which are too large cause the phase velocity to increase rapidly at low frequencies. In practice, the correct phase velocity is usually the first curve to turn upwards at low frequencies, although it is sometimes the first to turn downwards, and there is sometimes no clear choice.

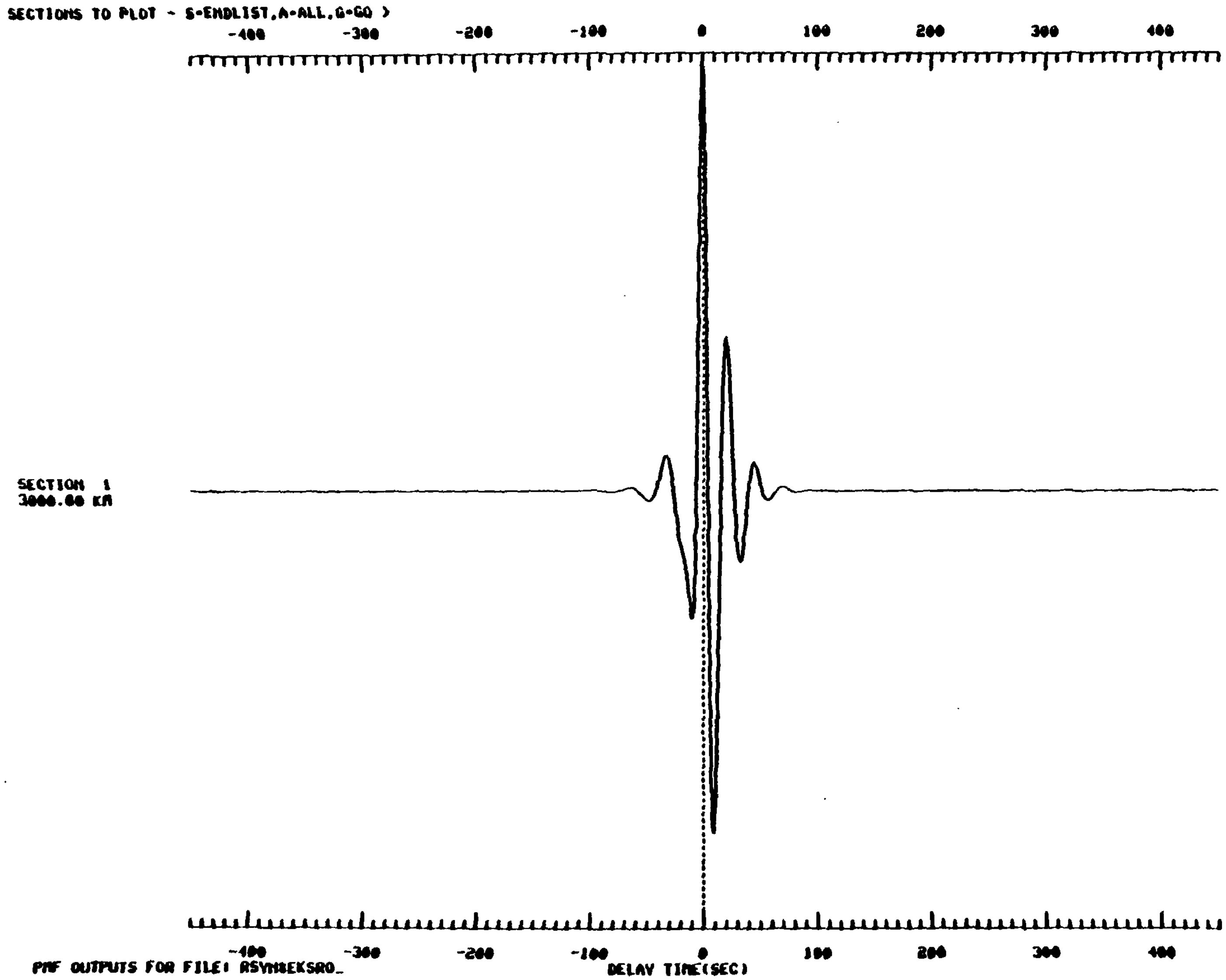


Figure 5. Phase matched filter output for synthetic seismogram. Energy is compressed to within ± 100 seconds of primary arrival time based on initial group velocity curve.

```
OPTION(H FOR HELP) >L
 IDX FREQ  PHASE-V

  21  .0098 3.956
  27  .0127 3.890
  34  .0161 3.853
  40  .0190 3.831
  46  .0220 3.811
  53  .0254 3.776
  59  .0283 3.729
  65  .0313 3.668
  72  .0347 3.581
  78  .0376 3.500
  85  .0410 3.410
  91  .0439 3.341
  97  .0469 3.281
 104  .0503 3.223
 110  .0532 3.181
 116  .0562 3.146
 123  .0596 3.112
 129  .0625 3.088
 135  .0654 3.068
 142  .0688 3.047
 148  .0718 3.033
 154  .0747 3.020
 161  .0781 3.007
 167  .0811 2.998
 174  .0845 2.989
 180  .0874 2.982
 186  .0903 2.976
 193  .0938 2.970
 199  .0967 2.965
 205  .0996 2.961
OPTION(H FOR HELP) >
```

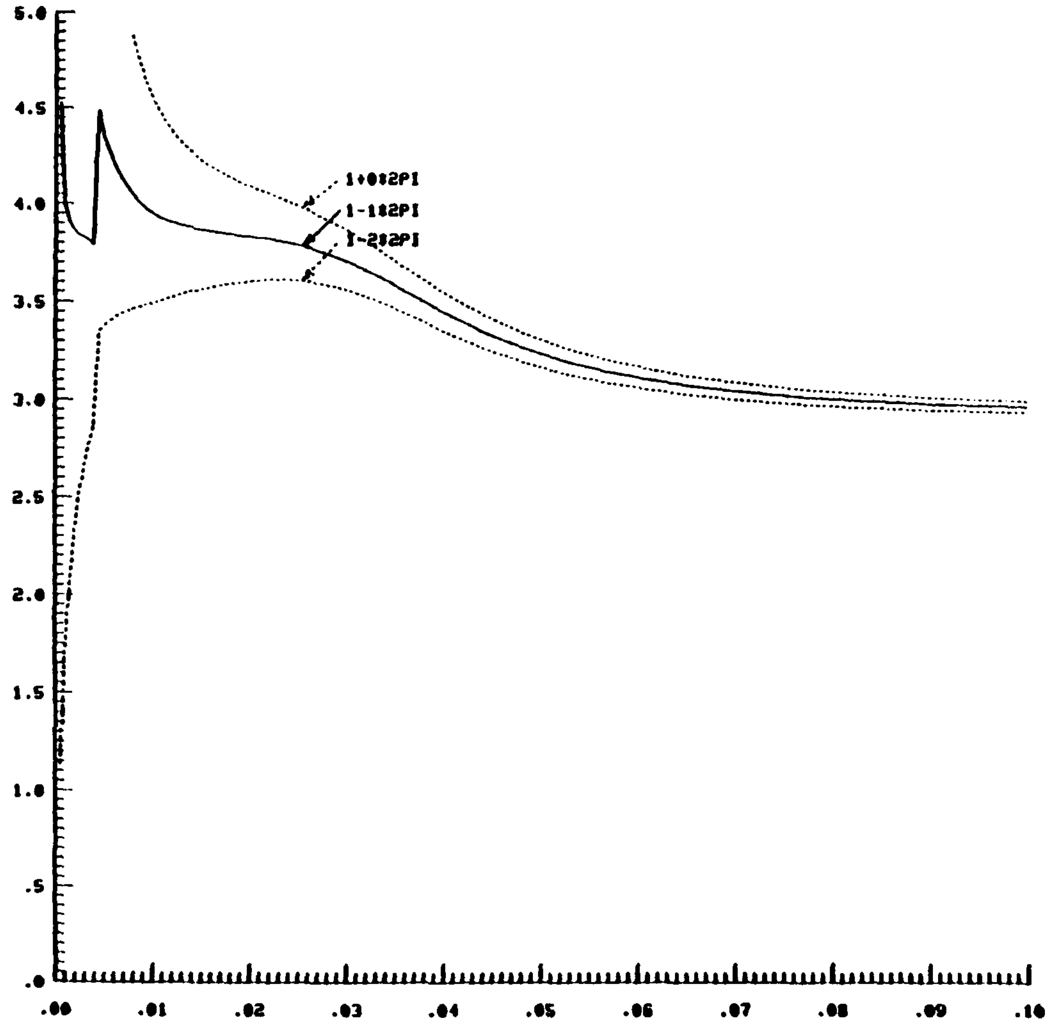


Figure 6. Phase velocities estimated by TELVEL for synthetic seismogram. Solid line is correct choice. Dashed lines differ by n $\pm$ 2π.

2. The true phase velocity is not very different from the group velocity at low frequencies, and is always greater than the group velocity at the lowest accurately determined frequency.

3. The phase velocity is approximately equal to 4 km/sec in most regions of the world at frequencies between .01 and .02 Hz.

If the choice of number of 2π's to add to the phase is not clear, save output files for more than one value and see which one leads to a reasonable inversion model. Also, processing of another seismogram for the same path may lead to a clearer choice of phase velocity.

An iterative procedure is used to refine the group velocity estimate. Usually two or three iterations will produce stable group velocity estimates which do not change from one iteration to the next (see Figure 7). It is a good idea to save the phase velocity plot, and group velocity plot on the final iteration for future reference. The choice of 2π's to be added to the phase may be easier after the group velocity has converged.

The final decision to be made is the choice of frequencies to output. These do not need to be the same as the initial narrow band filter frequencies. The range of frequencies should be large enough to include all data points that are reliable, but small enough to exclude unreliable data points. Two figures obtained in the processing help to identify the appropriate range. Points on the initial narrow band filtered group velocity plot with amplitudes less than 10 to 20 per cent (indicated by 1 and 2 on the plot) of the maximum amplitude are not likely to be reliable. On the final group velocity plot, portions of the curve at the ends, which have not stabilized, are not reliable. Portions of the group velocity curve which appear odd such as those which have a rapid decrease in velocity or an unusually high velocity at low frequency or rapid oscillations at high frequency should not be used. Periods longer than the time window used are also unreliable. It is important to

```
SEC8, OPTION (G-GO,N-NEWPLOT) ? )L
 IDX  FREQ OLD-V NEW-V

  1  .0098 3.708 3.606
  2  .0132 3.674 3.658
  3  .0161 3.727 3.732
  4  .0195 3.722 3.725
  5  .0225 3.636 3.639
  6  .0254 3.472 3.466
  7  .0288 3.280 3.289
  8  .0317 3.039 3.039
  9  .0347 2.834 2.827
 10  .0381 2.704 2.709
 11  .0410 2.621 2.619
 12  .0439 2.589 2.588
 13  .0474 2.586 2.586
 14  .0503 2.596 2.596
 15  .0532 2.613 2.614
 16  .0566 2.633 2.632
 17  .0596 2.655 2.656
 18  .0630 2.674 2.673
 19  .0659 2.696 2.696
 20  .0688 2.715 2.716
 21  .0723 2.731 2.730
 22  .0752 2.749 2.749
 23  .0781 2.764 2.765
 24  .0816 2.777 2.776
 25  .0845 2.791 2.791
 26  .0874 2.803 2.803
 27  .0908 2.814 2.812
 28  .0938 2.826 2.824
 29  .0967 2.832 2.831
 30  .1001 2.840 2.839
SEC8, OPTION (G-GO,N-NEWPLOT) ? )
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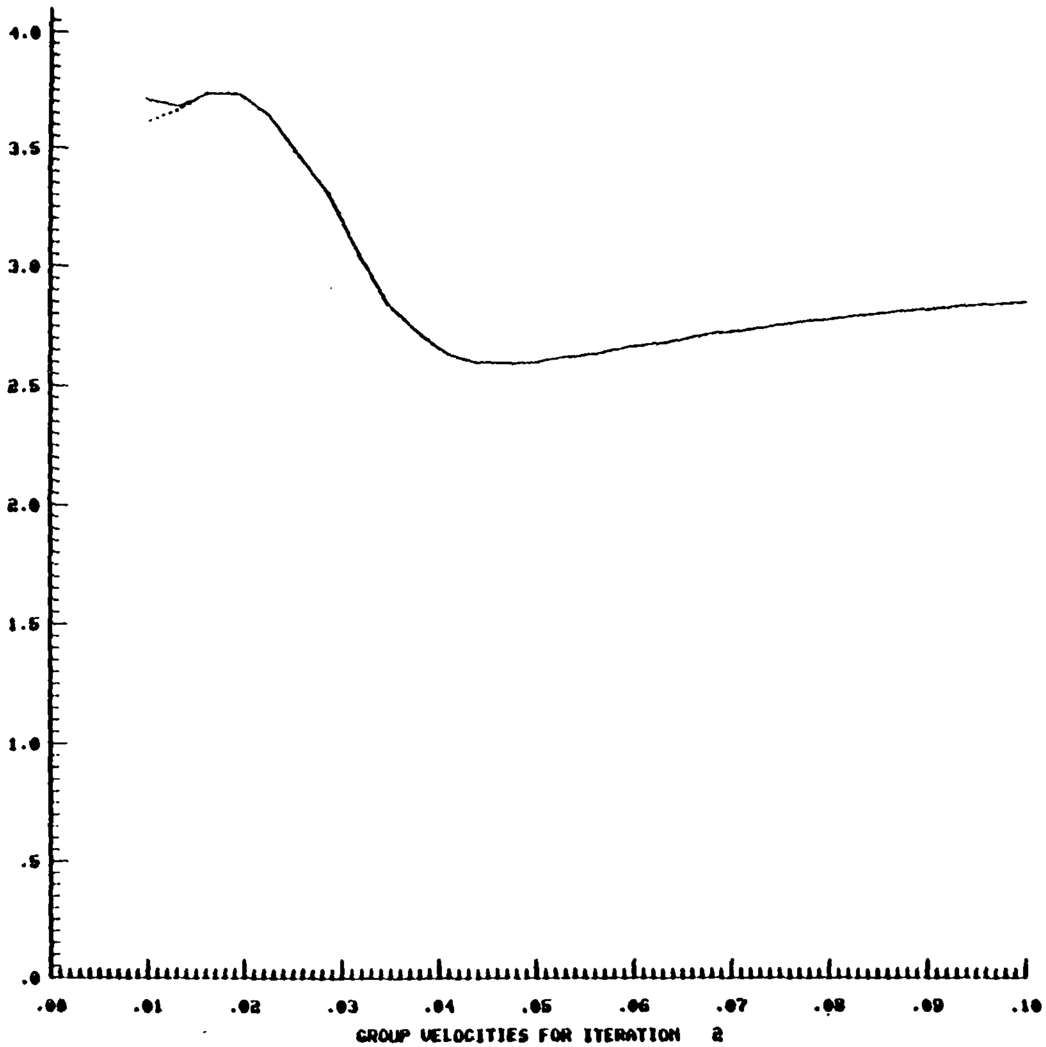


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SEC8, OPTION (G-GO,N-NEWPLOT) ? )1
```

Figure 7. Final group velocities obtained for synthetic seismogram by iterative application of phase matched filter.

obtain information at low frequencies since these frequencies determine the deep structure of the earth. For most SRO stations at distances of 2000 through 5000 kilometers, phase and group velocities may be reliably obtained from about .015 to .08 Hz. A convenient frequency spacing is .005 Hz. Phase and group velocities can almost always be obtained down to a minimum frequency of .02 Hz.

The output file from TELVEL contains the estimated phase and group velocities and the instrument corrected spectral amplitudes of the seismogram. The corrected amplitudes are an improvement over the Fourier amplitudes, since they are obtained from the compressed seismogram after the removal of noise and interfering phases.

The TELVEL output file also contains a space for the standard deviation of the phase and group velocity. TELVEL does not estimate errors in the velocities, so it simply outputs default values of zero. If more than one seismogram for the same path are processed, they can be averaged to get an improved estimate of phase and group velocities and to estimate uncertainties in the data. A small utility program (AVEDAT) is available which constructs a combined file in the format of a TELVEL file.

1.2.2 Inversion for Earth Structure

The TELVEL output file is in the proper format to be used by the second major code -- INVERT, which inverts the phase and group velocities for the average shear velocity structure along the path, and which uses the amplitudes to estimate the Q structure of the path.

Program INVERT has been designed to require a minimum of operator input. A starting model is automatically generated from the input data. The final model is independent of the starting model, but it is important to choose a suitable range of depths appropriate for the resolution capability of the data.

Only the TELVEL output file is required for shear velocity inversion. One other file is needed for Q inversion. Assuming that the structure of the source region is approximately known independently from previous investigations, an eigenfunction file (generated for the source region structure by program SYNSRF) will be input at this stage.

INVERT is divided into three main sections — model generation, inversion, and analysis. Most of the time the only command necessary in the model generation section is RUN which causes model generation to performed. In the model generation section, the user can set a value of Poisson's ratio and the coefficients of Birch's law if desired. The inversion code only inverts for shear velocity while compressional velocity and density are constrained by these constants. The default values are appropriate for most of the earth and rarely need to be changed. Two features which are sometimes needed are the ability to set a discontinuity at a particular depth, and the ability to set the number of layers used in the inversion. The default number of layers is 20. A smaller number of layers will result in a faster, but less accurate inversion.

In many cases a discontinuity may be required to match the data, but its depth is not usually known in advance. The best plan is to run the inversion section and insert a discontinuity where the resulting model shows a strong velocity gradient.

The first step in the inversion is to constrain the smoothness of the model defined by the number of degrees of freedom (command DF) allowed. A small value of DF produces a smooth model while a higher value produces a better data fit. A good value to start with is a DF of 4.

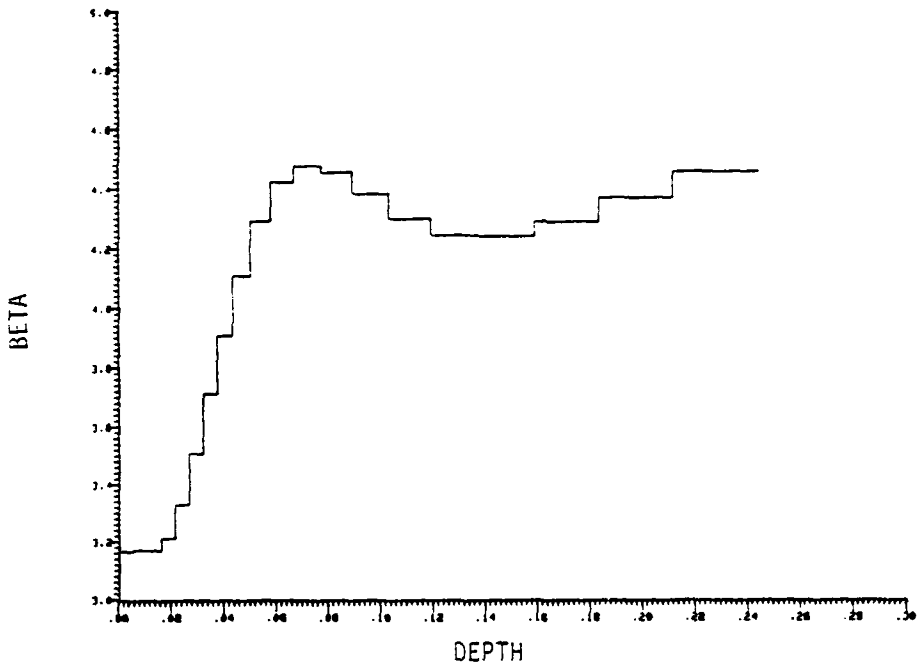
The command INVERT causes the first iteration of the inversion to be performed. This command causes partial derivatives $\partial c/\partial \beta$ and $\partial u/\partial \beta$ to be calculated from the initial (or current) model. It causes a set of matrices to be assembled from the partial derivatives, and performs a full singular value decomposition of the matrices. Finally it computes the exact nonlinear phase and group velocities for the estimated model with the DF specified initially. All of this requires quite a lot of computation and will take some computer time.

After the inversion has been performed, the command PLOT will plot the shear velocity structure while the command PLOT DATA will plot the linearized data fit.

The command DF has a new meaning after an inversion has been performed. A major advantage of the matrix decomposition is that new models for different values of DF may be generated without recomputing the matrices. Thus if the command DF 4 was given before inversion, the command DF 5 after inversion instantly produces the (linearized) model for a DF of 5. The commands PLOT and PLOT DATA again produce the model and data fit for the new DF (see Figure 8). This makes it very easy to pick the best value of DF. A second iteration can then be performed using this model as the new starting model. Usually three iterations with the same DF are sufficient for convergence.

An obvious question is how to choose the best model. The answer is to use a DF high enough to get a good data fit, but small enough to prevent oscillations of the shear velocity model, and to yield a smooth fit to the data. Usually a DF of about 5 gives a good model. With good quality data such as the SRO data a DF of 6 may be used, while less accurate data may only allow a DF of 4 (DF need not be an integer).

One other choice must often be made during inversion. It may be necessary to include a discontinuity in the model. The most common place a discontinuity is needed is at the crust-mantle boundary. The proper location for the discontinuity may be determined by the midpoint of a sharp gradient which appears in the shear velocity model. Within the inversion section a discontinuity may be added by specifying the number of the layer above the desired discontinuity, or it may be specified by depth by returning to the model generation section (this is unnecessary unless the user requests a specific depth which does not coincide with a layer boundary). If higher frequency data are available, as it may be for WWSSN instruments at distances less than 1000 kilometers, it may be necessary to include a shallow discontinuity in the upper few



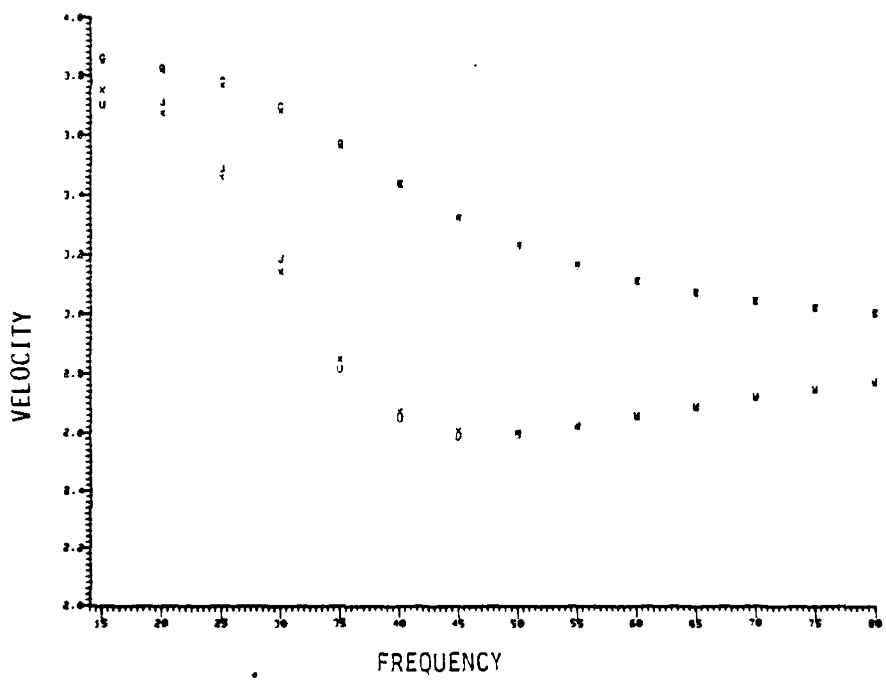


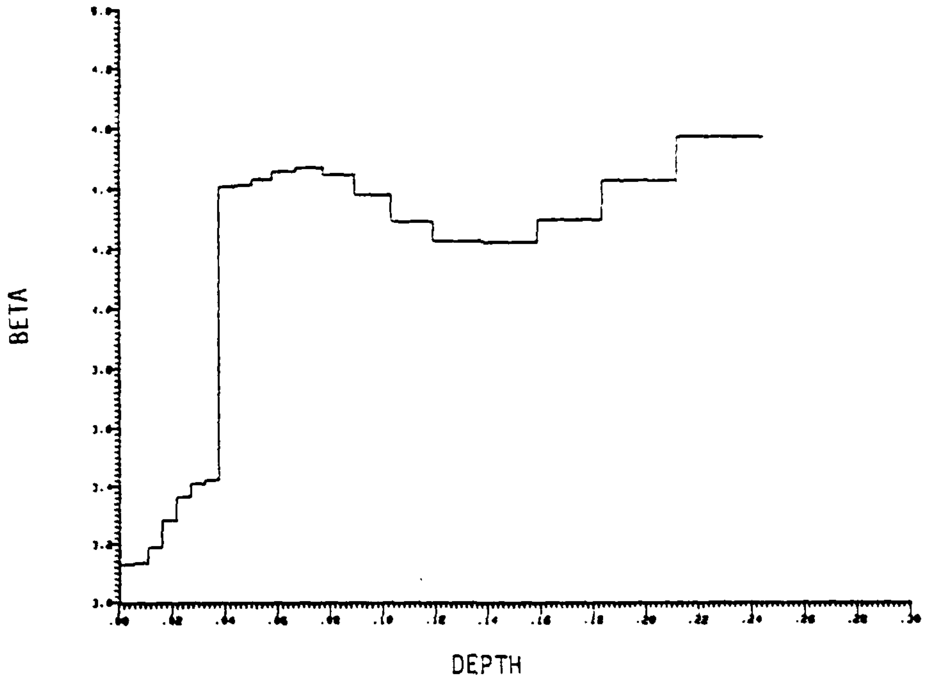
Figure 8. Shear velocity structure obtained by inverting dispersion curves produced by TELVEL from the synthetic seismogram, together with linearized data fit. The strong gradient from 20 to 60 km indicates a possible discontinuity. This model is shown for the second iteration using a DF of 5.0.

kilometers. It may be difficult to define the proper depth, since the phase and group velocities may lose accuracy at the high frequencies needed to resolve shallow depths. When the presence of this layer is indicated, it is often essential. The NTS-Tucson seismograms, for example, absolutely cannot be matched without a shallow low velocity, low Q layer in the upper two kilometers (Bache, T. C., W. L. Rodi, and D. G. Harkrider (1978)).

After the last iteration has been performed, give the command END to finalize the inversion and go to the analysis section. Here you can make final plots of the model, and the true nonlinear data fit (Figure 9). You can also print the data fit, variances and spreads for the final model.

One more calculation is required to obtain the complete earth model -- the Q structure needs to be found. The program does this by computing a synthetic seismogram (actually an unattenuated synthetic spectrum) at the observed frequencies and taking the ratio with the observed spectrum. The logarithm of the ratio is equal to a constant (the moment) plus a frequency dependent attenuation coefficient. In effect the level of the spectral ratio gives the moment, while the shape of the spectral ratio as a function of frequency gives the attenuation coefficients which can be inverted for the Q structure. As mentioned before, if an eigenfunction file is available for the source region, the program will generate the synthetic spectrum using these eigenfunctions for the source region and using the inverted structure for the path. The program uses the spectral ratio and inverts for log moment and β/Q simultaneously.

The spectral amplitudes are never known as accurately as the phase and group velocities, so a lower DF must be used for Q inversion. The minimum possible DF is 2. A DF of 2 will produce Q proportional to β in all layers. An important function of the Q inversion is in fact to smooth the spectral ratios and the attenuation coefficients. It is usually necessary to use a DF between 2 and 3. Higher DF's result in unrealistic Q structures. Discontinuities are not allowed for Q inversion, and are not used even if they were used in the velocity inversion.



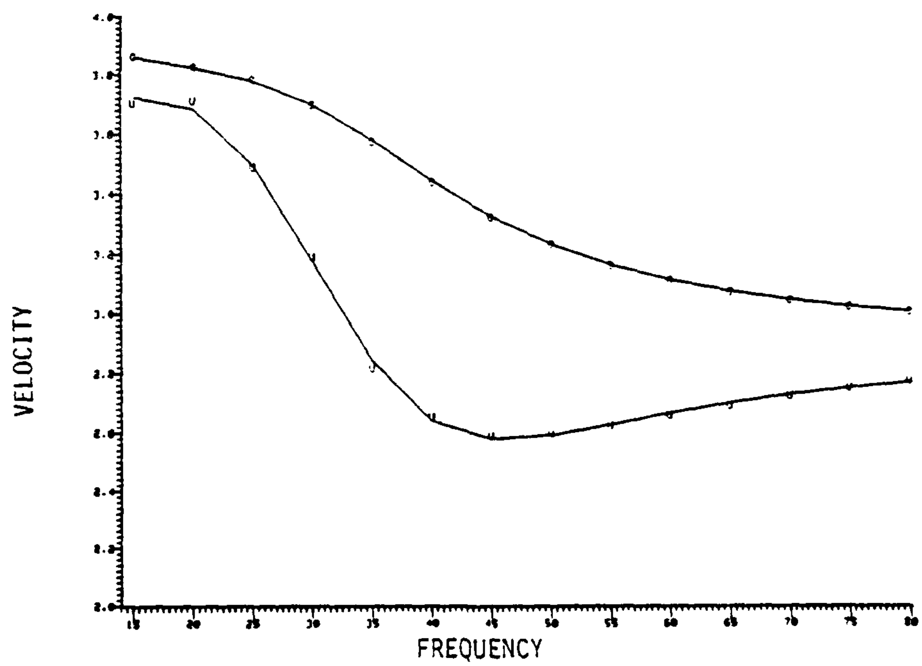


Figure 9. Final model obtained using a DF of 6.0 and a single discontinuity (compare with Figure 1) together with data fit. The intermediate layer from 30 to 50 km has been split by the single discontinuity. The dispersion curves are an excellent fit to the data.

Q inversion is linear, and takes little computer time. Matrices are formed and decomposed on the first iteration, so the best Q model may be quickly found. Again the command PLOT plots the Q model while the command PLOT DATA plots the spectral ratios and corresponding data fit. The spectral ratios should look like an upward sloping line (see Figure 10). If the data points do not have an upward slope, it means the attenuation coefficients decrease with frequency and no Q structure will fit the data. If this happens, there is probably something wrong with the inversion, or with the data.

When the Q inversion is performed, the estimated moment and of the explosion are printed out. Save these numbers, since they are not printed out again.

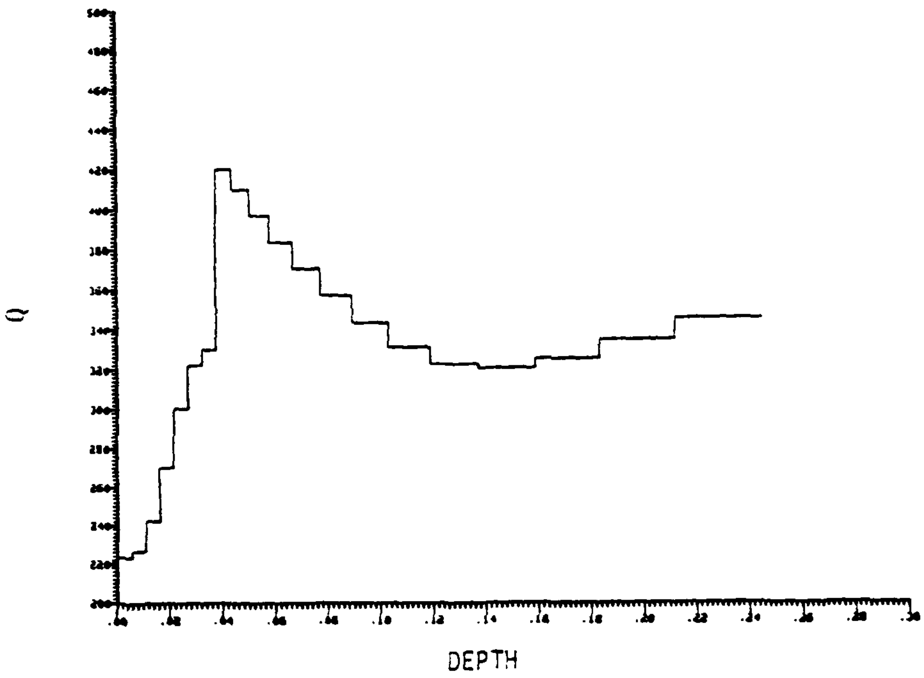
Since the Q inversion produces a smoothed β/Q model, it will not reveal any true discontinuities in Q in the earth. In particular, it will not usually produce a very low Q at the surface. If high frequency data have been used, it may be necessary to add a low Q layer near the surface after the inversion to reduce high frequency ringing.

Once the inversion is completed the final step is to output a structure file. The structure file is a formatted file, which is in the format of an input file to SYNSRF.

1.2.3 Generation of Synthetic Seismograms and Excitation Functions

The third stage of the path correction procedure is to use the program SYNSRF to generate an eigenfunction file, and to make a synthetic seismogram as the final test of the procedure.

SYNSRF is divided into four main sections. The first section requires input of a model (structure) file and a choice of frequencies for the calculation of phase velocities. The second section calculates group velocities, eigenfunctions and related parameters. The third section calculates a synthetic seismogram. The fourth section allows prints and plots of the seismogram, spectra and dispersion curves.



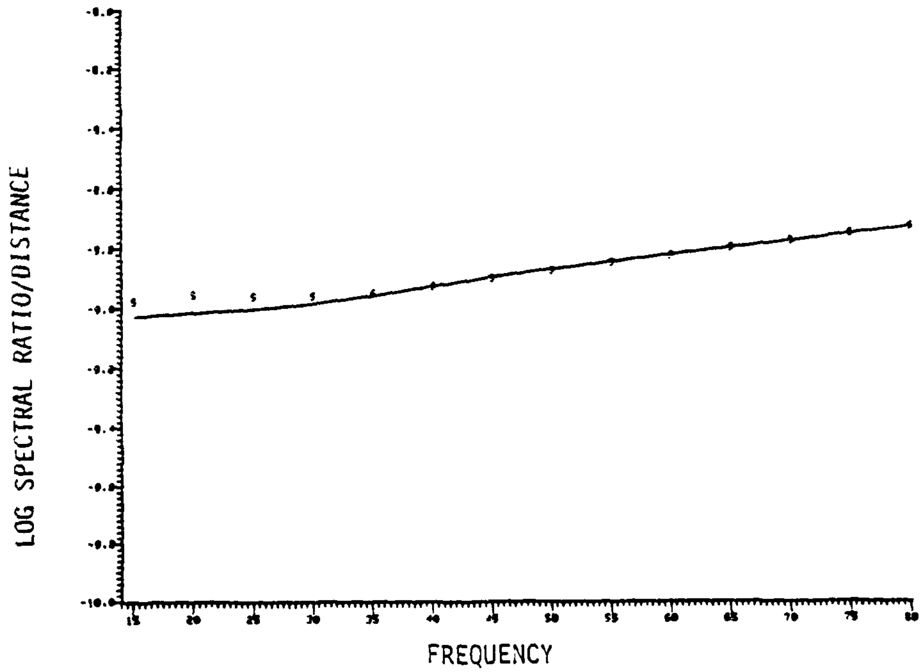


Figure 10. Q structure and data fit obtained using a DF of 2.5. The Q model is a smoothed version of the true Q model (Figure 1) while the data is the ratio of synthetic (unattenuated) to observed spectra. The moment is obtained simultaneously. For this example the moment differed by 2% from the true moment.

SYNSRF is designed to be easy to use and to make it easy to correct mistakes. If you run one of the sections and use an incorrect number, or forget to output a file, simply back up, make the change and run this section again. None of the sections is very time consuming and all previous inputs are remembered (except for output files, since they are closed after each section is run).

The essential input in part 1 of SYNSRF is the model file (the output file from INVERT). The default set of frequencies is 100 frequencies evenly spaced from .002 to .2 Hz. In most cases, this will be a good range of frequencies. For observations at close range (< 1000 km) with an instrument that does not filter out higher frequencies, it may be necessary to use frequencies from .005 to .5 Hz instead. The program is currently dimensioned to allow 100 frequencies and three modes. After the model file is read in in Part 1, the program looks through the shear velocities to estimate root search parameters (minimum and maximum phase velocities and a step size). The default values are almost always adequate, especially for the fundamental mode. If the step size chosen is too large, a root may be missed. This will show up as a glitch in the dispersion curve.

The command RUN causes dispersion curves to be calculated and leaves the program in Part 2. The only inputs needed in Part 2 are the source depth and a file name for the eigenfunction output file. The default source depth is 1 kilometer. If the structure being used is the path structure, then the source depth is irrelevant. It is necessary to specify an eigenfunction file name here. This file will be used in two ways. It will be read back in Part 3 if a separate source region is used, and it contains all of the information needed to construct the Green's function that is the final path correction.

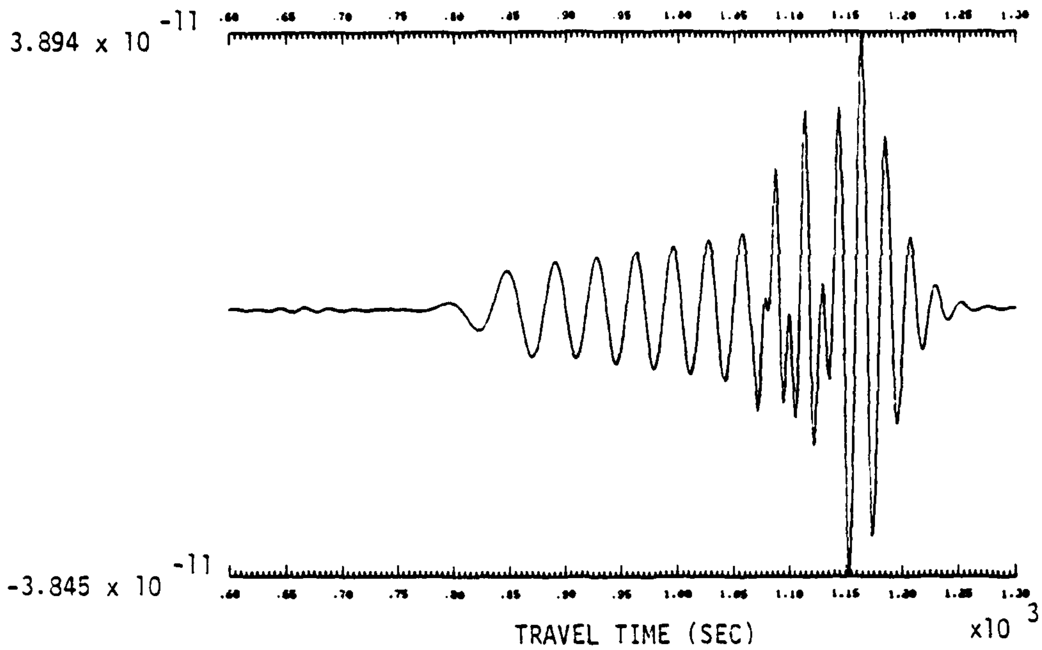
The command RUN now causes the eigenfunctions to be generated and leaves the program in Part 3. You can make a plot of the dispersion curves (phase and group velocities) here to compare with the observations. Make this plot before reading in a new source region eigenfunction file, since the velocities plotted are the source region velocities.

Several quantities must be input here to make a synthetic seismogram. If you are using separate source and path regions, an eigenfunction file for the source region and the eigenfunction file for the path must be read in. An instrument response must be read in, preferably using the polynomial coefficients that were used in TELVEL (on a formatted rather than a REALIO file, see file format appendix). The distance and time window must be specified here. After the distance is set, the time window is estimated by the program using the group velocities. For the purpose of making a path correction, however, it may be preferable to use the time window of the original seismogram to make the comparison easier.

The command RUN now causes a seismogram for an explosion with a Ψ_∞ of one cubic meter to be generated, and leaves the program in Part 4. Then plots of the seismogram and spectrum may be made, a run summary may be obtained, and surface wave magnitudes may be computed.

The seismogram plotted here should look like the original seismogram (see Figure 11) after removal of noise and multipathing. The amplitude should differ from the original amplitude by a factor approximately equal to the Ψ_∞ estimated in the inversion calculation.

The last step in the procedure is to transform the eigenfunction file into a form usable by a moment tensor inversion program. A short program EXCITE turns the eigenfunction file into a formatted file using the excitation function notation of Kanamori and Given (1981), as explained in Appendix 4.



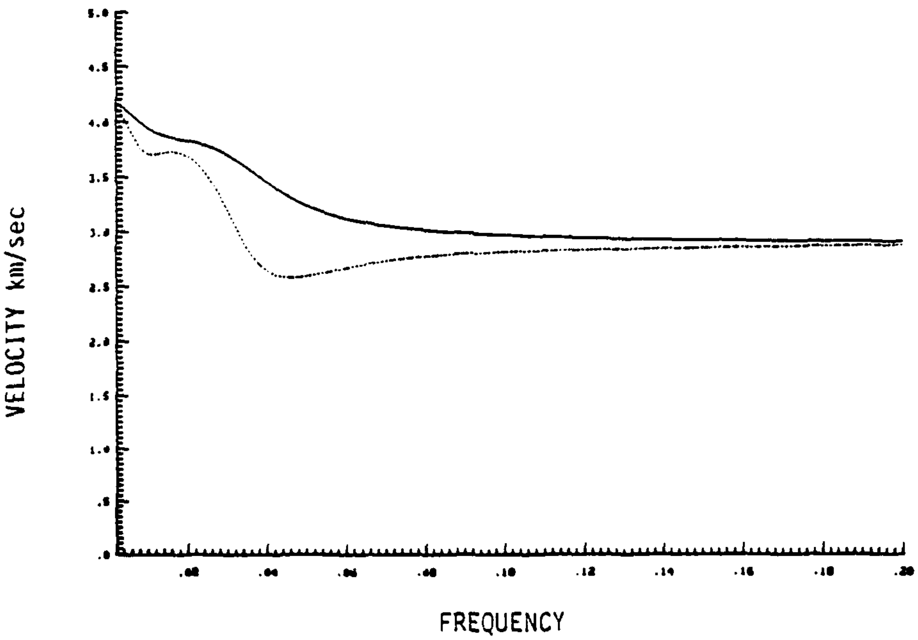


Figure 11. Synthetic seismogram generated using the structure output by INVERT, together with phase and group velocity dispersion curves. Compare with Figure 2.

II. SHAGAN RIVER-SRO PATH CORRECTIONS

In this section we describe, in brief, the processing of explosion seismograms recorded at seven SRO stations. For each path there is a description of the analysis including an estimate of confidence for each path correction, plus five figures. The first figure is a narrow band filter estimate of the group velocity for one seismogram along each path. The NBF estimate often shows up problems such as extreme multipathing, high noise level, or bifurcated group velocity curves which may cause difficulty in the data analysis. The second figure is a plot of the data fit, solid lines being the calculated phase and group velocity curves from our final structure while letters U (group velocity) and C (phase velocity) are observed data points. The third figure is a plot of shear velocity versus depth for the structure obtained by inversion, the fourth is a plot of Q versus depth, while the last figure is a listing of velocities, densities, and Q obtained for each model. The three events processed are explosions at the Shagan River test site which occurred on 2 December 1979 (No. 318), 29 November 1978 (No. 312), and 23 June 1979 (No. 313). The seismograms are shown in Figures 12 through 14.

In addition to obtaining a velocity and Q structure for each path, we also obtain an estimate of moment for each path. By assuming a known compressional velocity and density for the source region (we used $\alpha = 5000$ m/sec, $\rho = 2100$ kg/m^3), the result may be expressed in terms of Ψ_∞ using the relation $M_x = 4\pi\rho\alpha^2\Psi_\infty$. The results are listed in Table 1.

The last station is considerably less reliable than the first six for reasons that will be explained with the data. It is interesting to note that there seems to be a correlation between the estimated Ψ_∞ and the quality of the data. This may be an indication of energy lost due to scattering and non-plane layered effects along the travel path. It does not seem to result from application of the phase matched filter time window since synthetic seismograms made

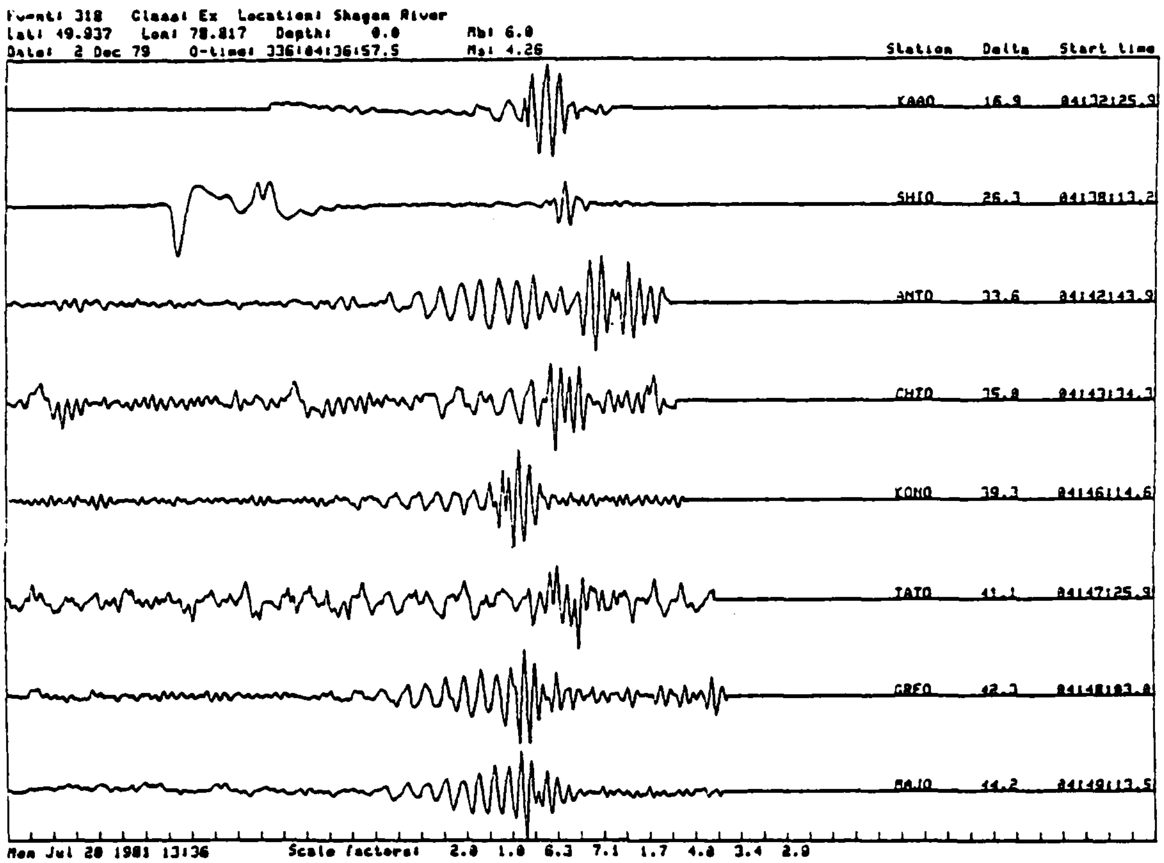


Figure 12. Seismograms recorded at SRO stations for Shagan River explosion number 318, December 2, 1979. Seismograms were processed to obtain path corrections for stations KAAO, SHIO, ANTO, CHTO, KONO, GRFO and MAJO. Before processing, a reduced time window was chosen to eliminate early arrivals and glitches and the seismograms were demeaned and detrended.

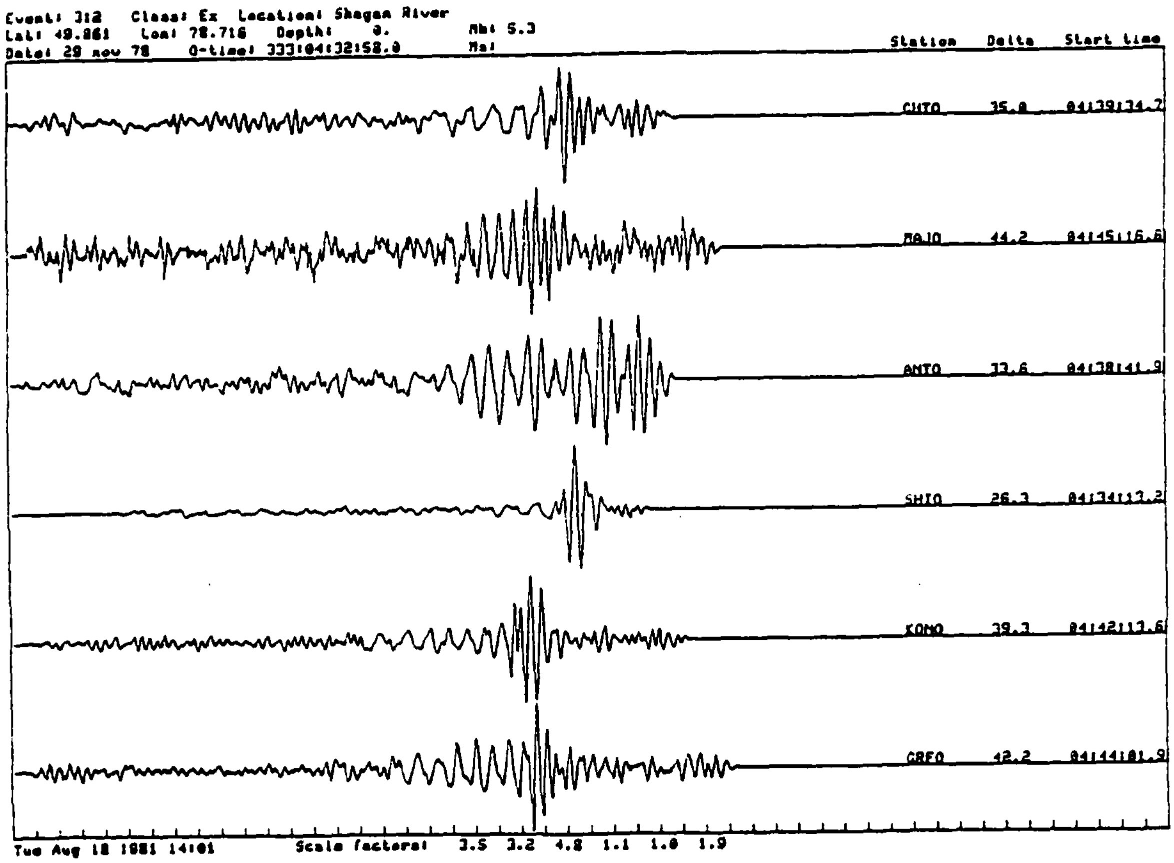


Figure 13. Seismograms recorded at SRO stations for Shagan River explosion number 312, November 29, 1978. Seismograms were processed to obtain path corrections for stations CHTO, MAJO, ANTO, SHIO, KONO, and GRFO.

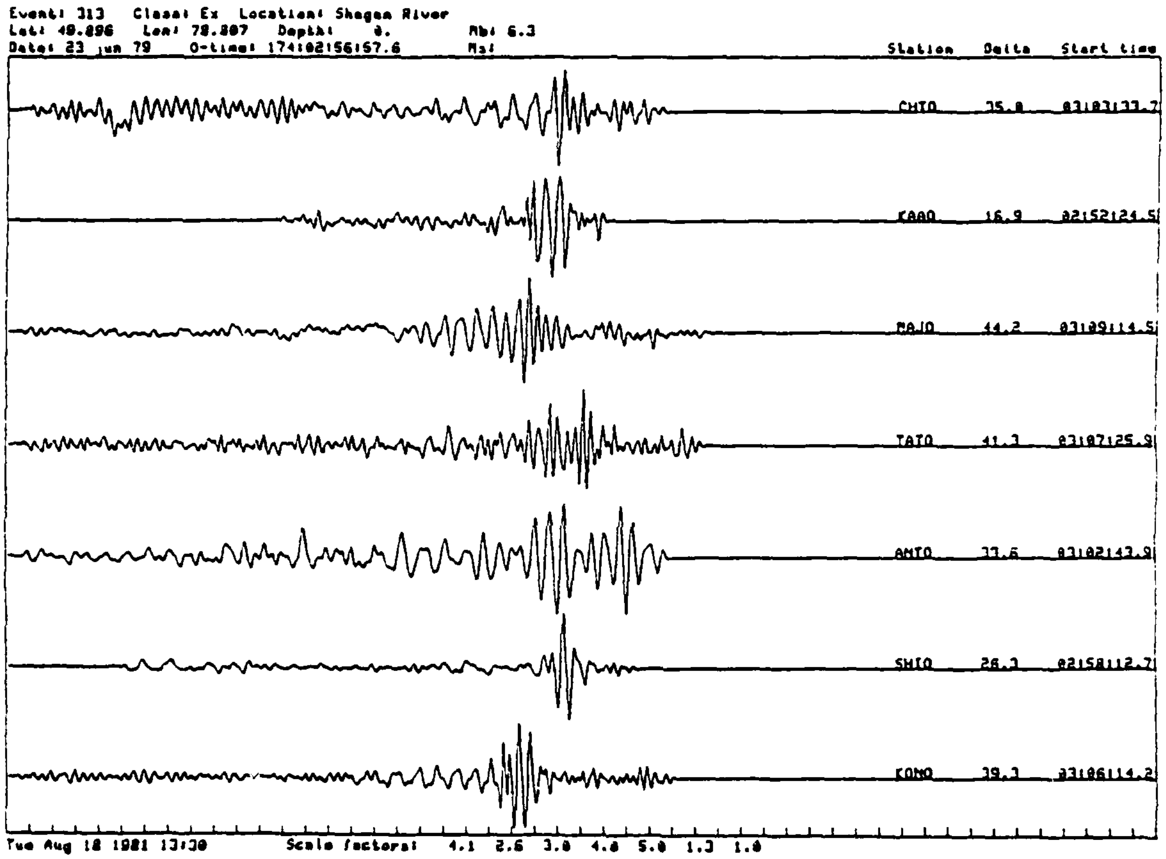


Figure 14. Seismograms recorded at SRO stations for Shagan River explosion number 313, June 23, 1979. Seismograms were processed to obtain path corrections for stations CHTO, MAJO, SHIO, and KONO. Processing of stations KAAO and ANTO was attempted, but excessive noise and multipathing made it difficult to obtain stable group velocity curves at those stations.

Table 1

ESTIMATED Ψ_{∞}

(MOMENT $\div$ 6.60 x 10^{11})

Station	Distance	Event No. 318	Event No. 312	Event No. 313
KONO	4370	15100	9980	15000
SHIO	2926	13400	9760	13400
MAJO	4918	13000	5100	8100
GRFO	4700	11800	6700	—
ANTO	3739	10300	5440	—
CHTO	3890	7200	5000	6700
KAAO	1885	5700	—	—

using the estimated values of Ψ_∞ are not consistently lower in amplitude than the observed seismograms (see Table 2). Of course, the estimates of Ψ_∞ also depend on the accuracy of the instrument gain. These seismograms were provided by Data Services at the Seismic Data Analysis Center (SDAC) after conversion to nanometers (at 20 seconds).

In general, the processing resulted in reasonable velocity structures and Q structures for most of the stations and should provide a good estimate of the path structure and attenuation.

Table 2

TIME DOMAIN AMPLITUDE COMPARISON

STATION	OBSERVED/SYNTHETIC AMPLITUDES (NM)		
	Event No. 318	Event No. 312	Event No. 313
KONO	765/725	460/479	736/720
SHIO	606/600	414/437	576/600
MAJO	371/378	134/148	248/236
GRFO	361/484	240/275	---
ANTO	192/156	94/83	143/---
CHTO	174/249	132/173	178/232
KAAO	613/305	---	282/---

Figures 15.1 through 15.5 are on the following pages.

Figure 15. Path 1: SHAGAN-KONO

Distance: 4372 km
Azimuth: 72.6°
Instrument: ASRO-LP
Events Processed: 318, 312, 313

Description: This is an excellent station. A very clean group velocity curve was obtained with no evidence of multipathing or any observational problems.

SEC 8, OPTION(H-HELP) ?)1 L
GROUP VELS PICKED:

IDX	FREQ	GRPV	AMPL
1	.0104	4.051	.033
2	.0137	4.015	.113
3	.0167	3.950	.172
4	.0199	3.837	.253
5	.0230	3.696	.321
6	.0263	3.549	.392
7	.0294	3.417	.474
8	.0324	3.299	.526
9	.0357	3.192	.578
10	.0391	3.128	.658
11	.0427	3.080	.780
12	.0454	3.051	.908
13	.0479	3.040	.985
14	.0504	3.036	1.000
15	.0529	3.037	.965
16	.0554	3.040	.897
17	.0578	3.044	.808
18	.0604	3.052	.712
19	.0637	3.060	.627
20	.0671	3.068	.566
21	.0706	3.076	.524
22	.0735	3.082	.491
23	.0766	3.088	.459
24	.0789	3.093	.422
25	.0810	3.098	.381
26	.0831	3.103	.336
27	.0852	3.108	.293
28	.0877	3.111	.253
29	.0902	3.113	.217
30	.0925	3.114	.186

SEC 8, OPTION(H-HELP) ?)

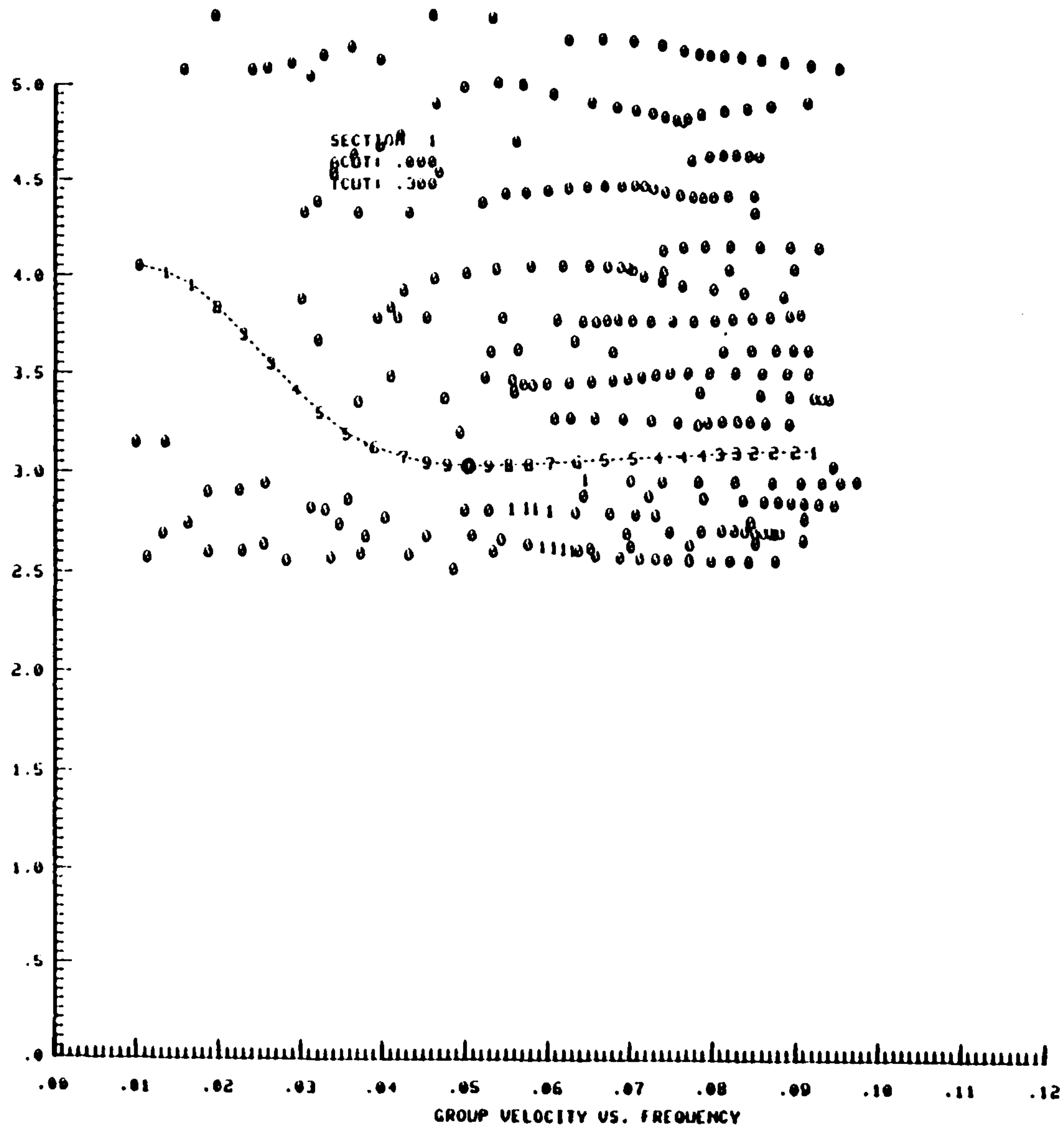


Figure 15.1.

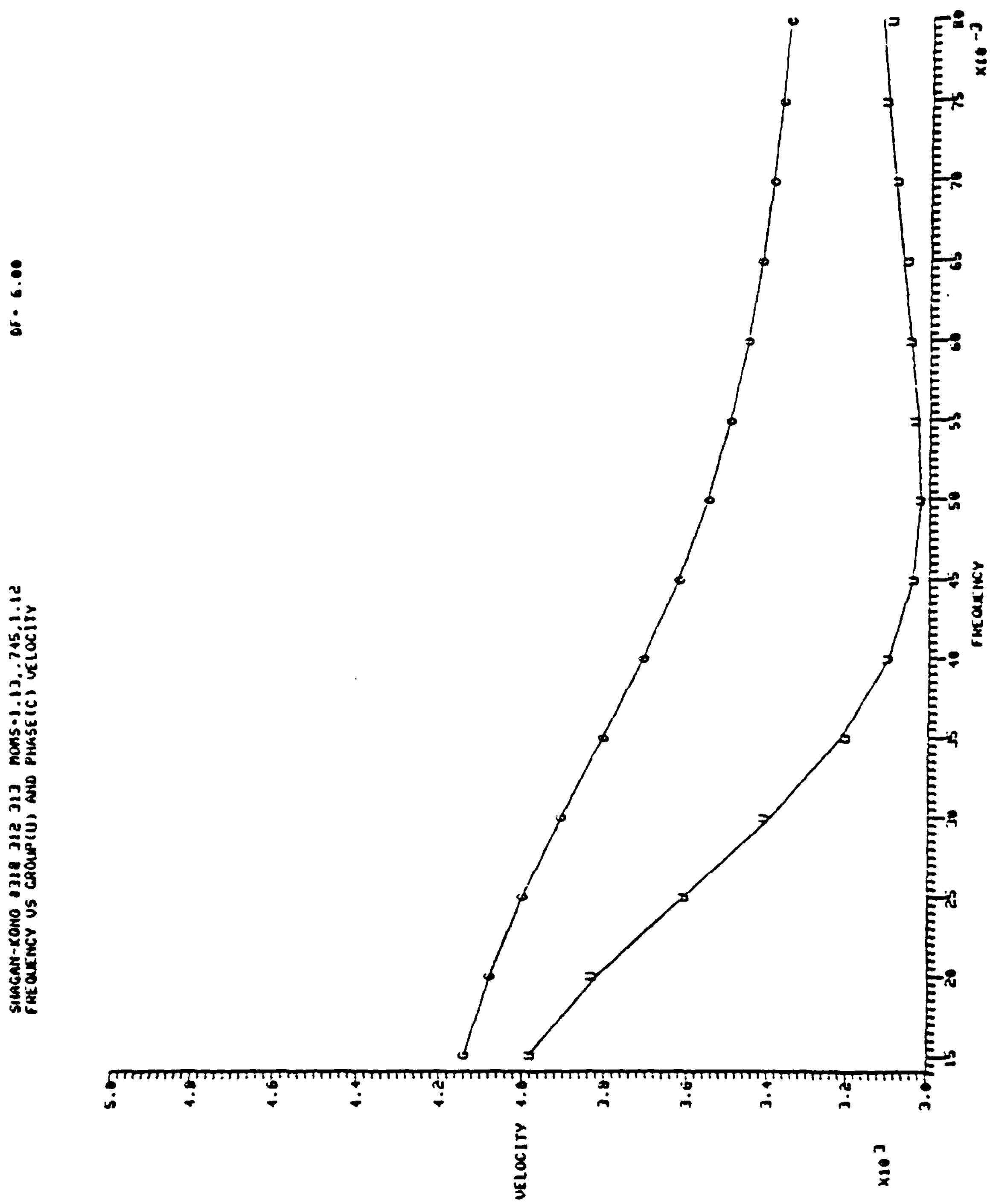

SHAGAN-KONO #318 312 313 MOMS-1.13,.745,1.12
FREQUENCY VS GROUP(U) AND PHASE(C) VELOCITY
DF- 6.00
VELOCITY
X10 3
FREQUENCY
X10 -3
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
15
20
25
30
35
40
45
50
55
60
65
70
75
80

Figure 15.2.

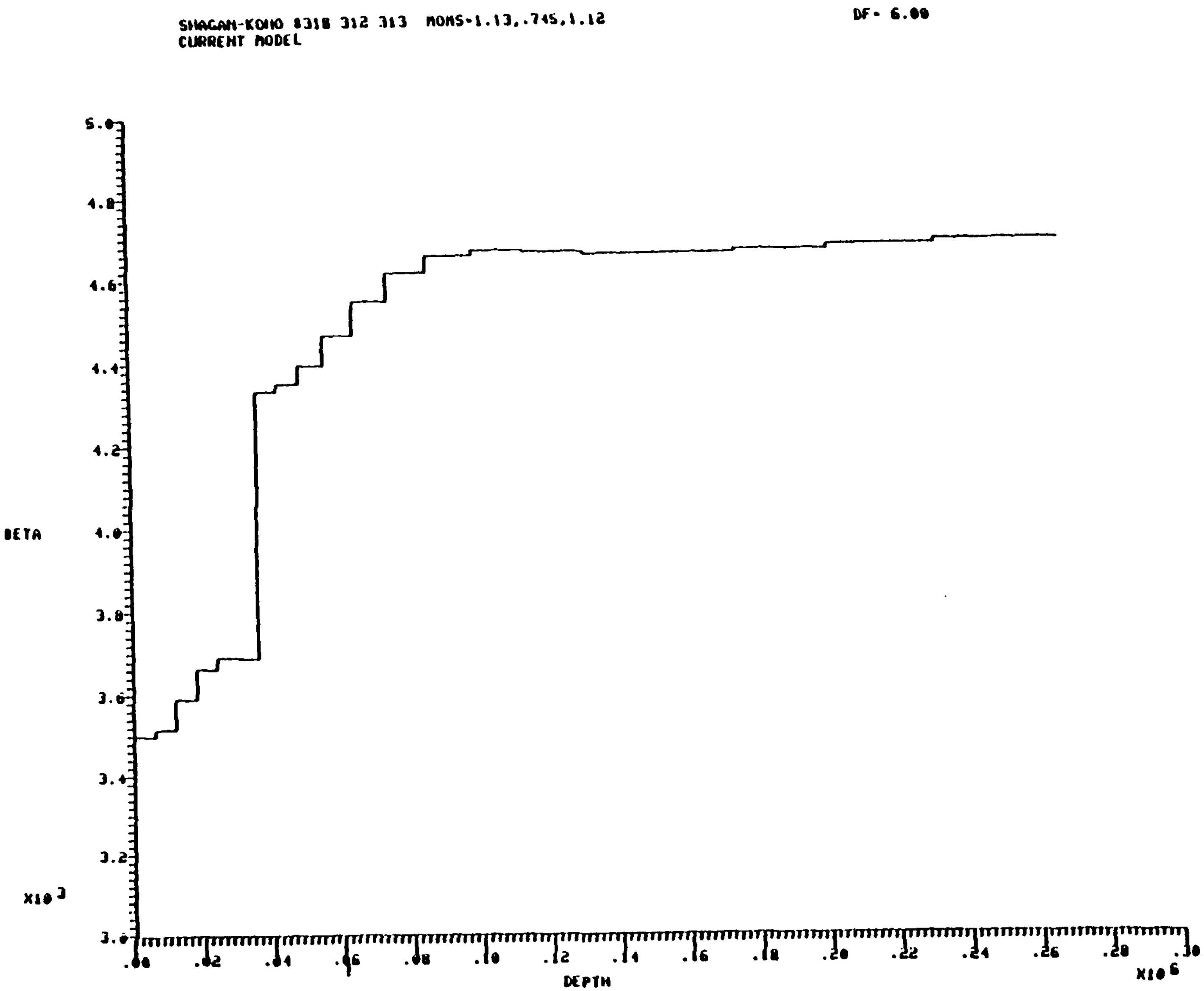

SHAGAN-KONO #318 312 313 MOMS-1.13,.745,1.12
CURRENT MODEL
DF- 6.00
BETA
X10 3
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
DEPTH
X10 6
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30

Figure 15.3.

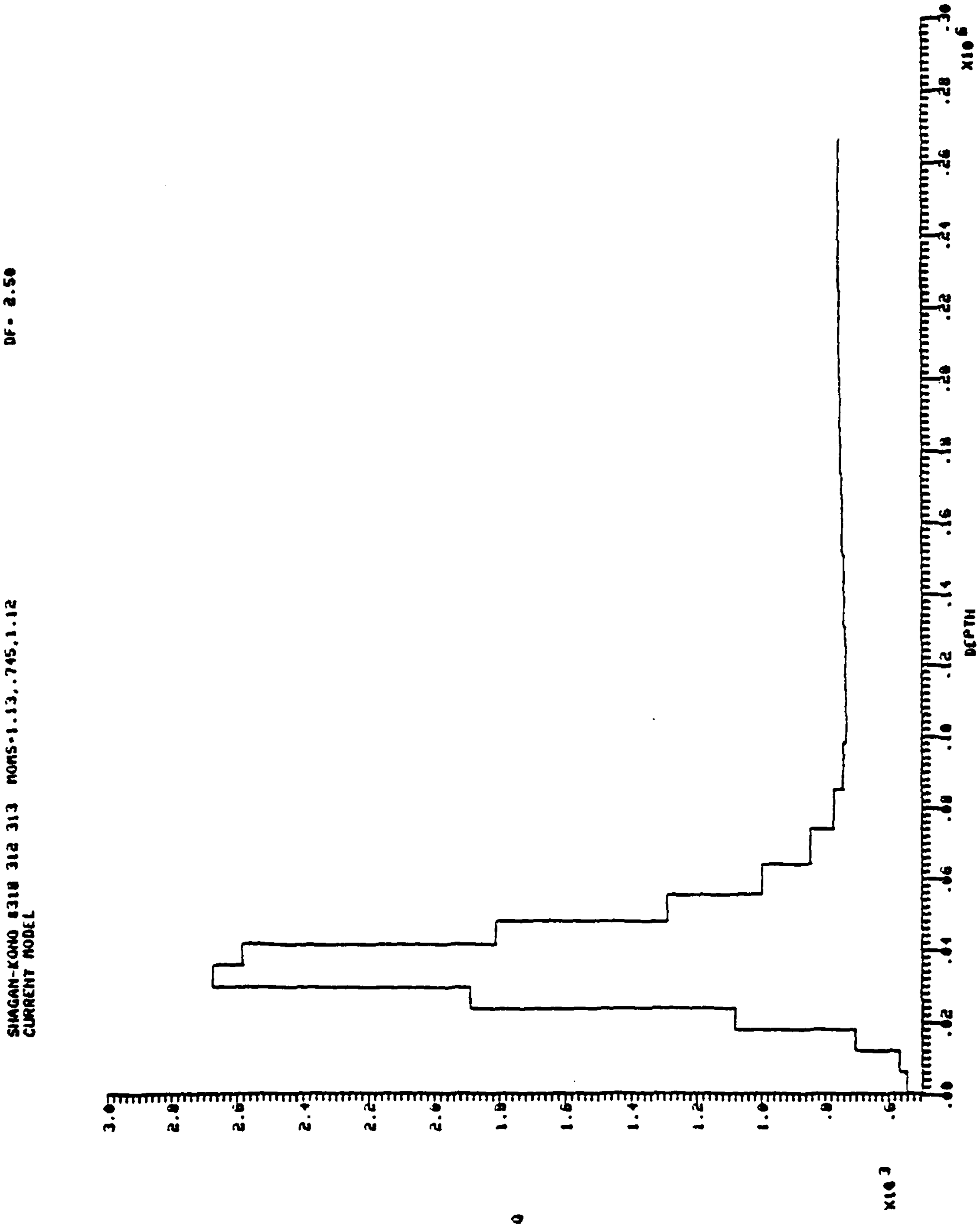

SHAGAN-KONO 8318 312 313 MOMS=1.13,.745,1.12
CURRENT MODEL
DF= 2.50
DEPTH
X10^6
Q
X10^3

Figure 15.4

SHAGAN-KONO STRUCTURE

I	DEPTH	THICK	ALPHA	BETA	RHO	QCM
1	5.986+003	5.985+003	6.230+003	3.497+003	2.673+003	5.429+002
2	1.197+004	5.985+003	6.260+003	3.514+003	2.684+003	5.650+002
3	1.796+004	5.985+003	6.392+003	3.538+003	2.732+003	7.035+002
4	2.394+004	5.985+003	6.522+003	3.661+003	2.750+003	1.083+003
5	2.993+004	5.985+003	6.574+003	3.690+003	2.798+003	1.558+003
6	3.591+004	5.985+003	6.569+003	3.637+003	2.797+003	2.673+003
7	4.190+004	5.985+003	7.718+003	4.332+003	3.216+003	2.552+003
8	4.332+004	6.417+003	7.750+003	4.350+003	3.227+003	1.810+003
9	5.572+004	7.400+003	7.928+003	4.394+003	3.256+003	1.291+003
10	6.425+004	8.533+003	7.956+003	4.466+003	3.303+003	9.990+002
11	7.409+004	9.840+003	8.101+003	4.547+003	3.356+003	8.473+002
12	8.544+004	1.134+004	8.224+003	4.616+003	3.400+003	7.740+002
13	9.853+004	1.308+004	8.255+003	4.656+003	3.426+003	7.431+002
14	1.136+005	1.508+004	8.314+003	4.667+003	3.434+003	7.344+002
15	1.310+005	1.740+004	8.307+003	4.663+003	3.431+003	7.359+002
16	1.511+005	2.006+004	8.297+003	4.657+003	3.427+003	7.409+002
17	1.742+005	2.313+004	8.298+003	4.658+003	3.429+003	7.463+002
18	2.009+005	2.668+004	8.311+003	4.665+003	3.432+003	7.506+002
19	2.317+005	3.077+004	8.329+003	4.675+003	3.439+003	7.539+002
20	2.672+005	3.548+004	8.347+003	4.685+003	3.445+003	7.561+002

Figure 15.5.

Figures 16.1 through 16.5 are on the following pages.

Figure 16. Path 2: SHAGAN-SHIO

Distance: 2927 km
Azimuth: 340.8°
Instrument: SRO-LP
Events Processed: 318, 312, 313

Description: This is an excellent station. There is a small branch in the group velocity curve at 0.065 Hertz, but otherwise it is very clean. The group velocities seem stable and inversion results in a reasonable structure with a relatively low Q.

```
SEC 0, OPTION(H-HELP) ? )L
SEC 0, OPTION(H-HELP) ? )1 L
 GROUP VELS PICKED:
IDX  FREQ  GRPV  AMPL

  1  .0092 3.662  .041
  2  .0131 3.528  .086
  3  .0170 3.409  .128
  4  .0196 3.311  .169
  5  .0229 3.156  .197
  6  .0268 3.020  .264
  7  .0305 2.911  .419
  8  .0334 2.861  .635
  9  .0360 2.838  .628
 10  .0386 2.830  .940
 11  .0413 2.828 1.000
 12  .0440 2.830 1.000
 13  .0468 2.834  .965
 14  .0497 2.839  .913
 15  .0526 2.842  .852
 16  .0551 2.842  .777
 17  .0574 2.840  .687
 18  .0593 2.836  .580
 19  .0610 2.829  .464
 20  .0626 2.815  .354
 21  .0658 2.794  .267
 22  .0689 2.778  .210
 23  .0723 2.768  .171
 24  .0749 2.761  .140
 25  .0768 2.758  .113
 26  .0778 2.757  .088
 27  .0790 2.764  .067
 28  .0824 2.774  .051
 29  .0863 2.780  .040
 30  .0906 2.783  .033
SEC 0, OPTION(H-HELP) ? )
```

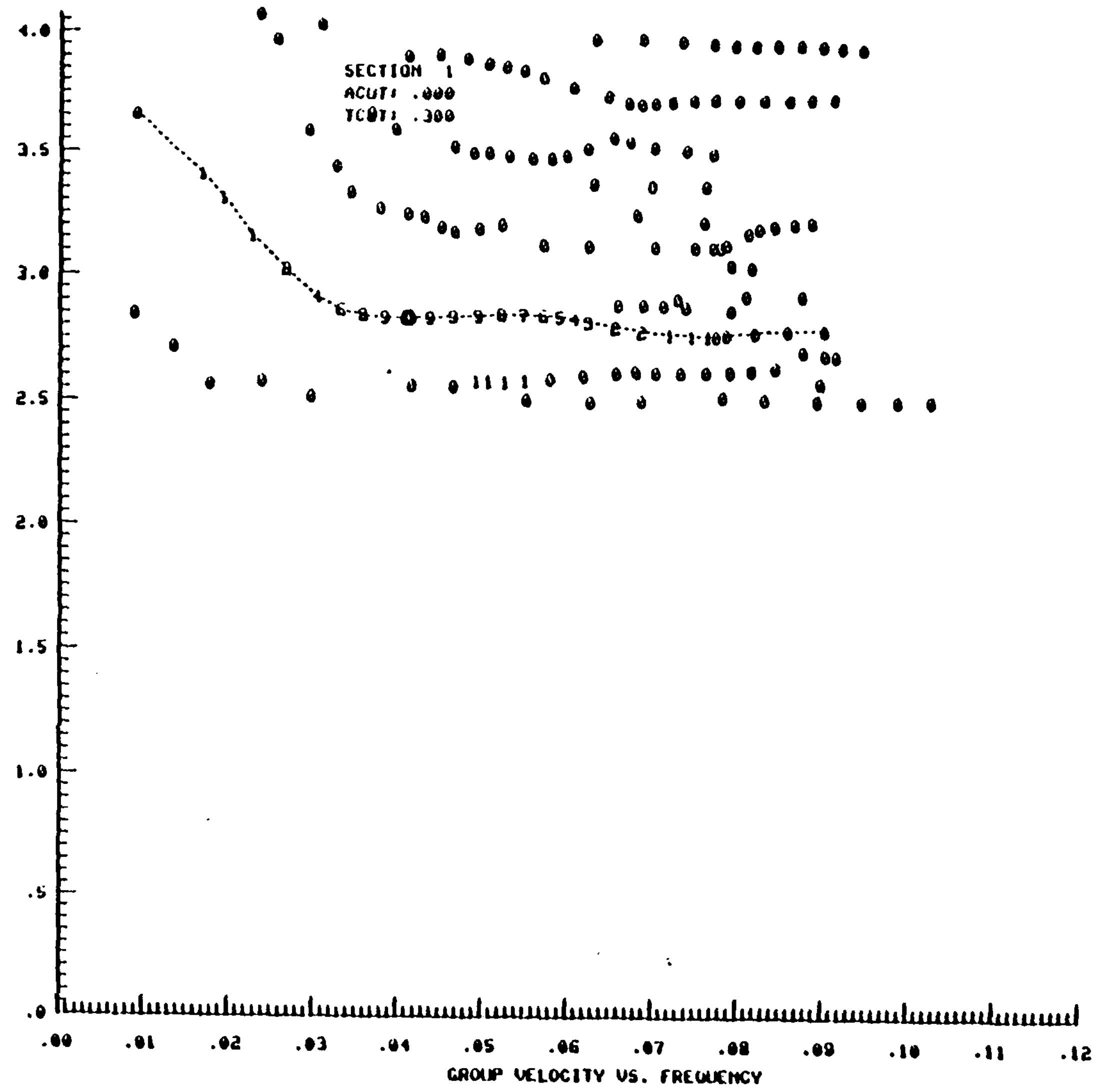


Figure 16.1.

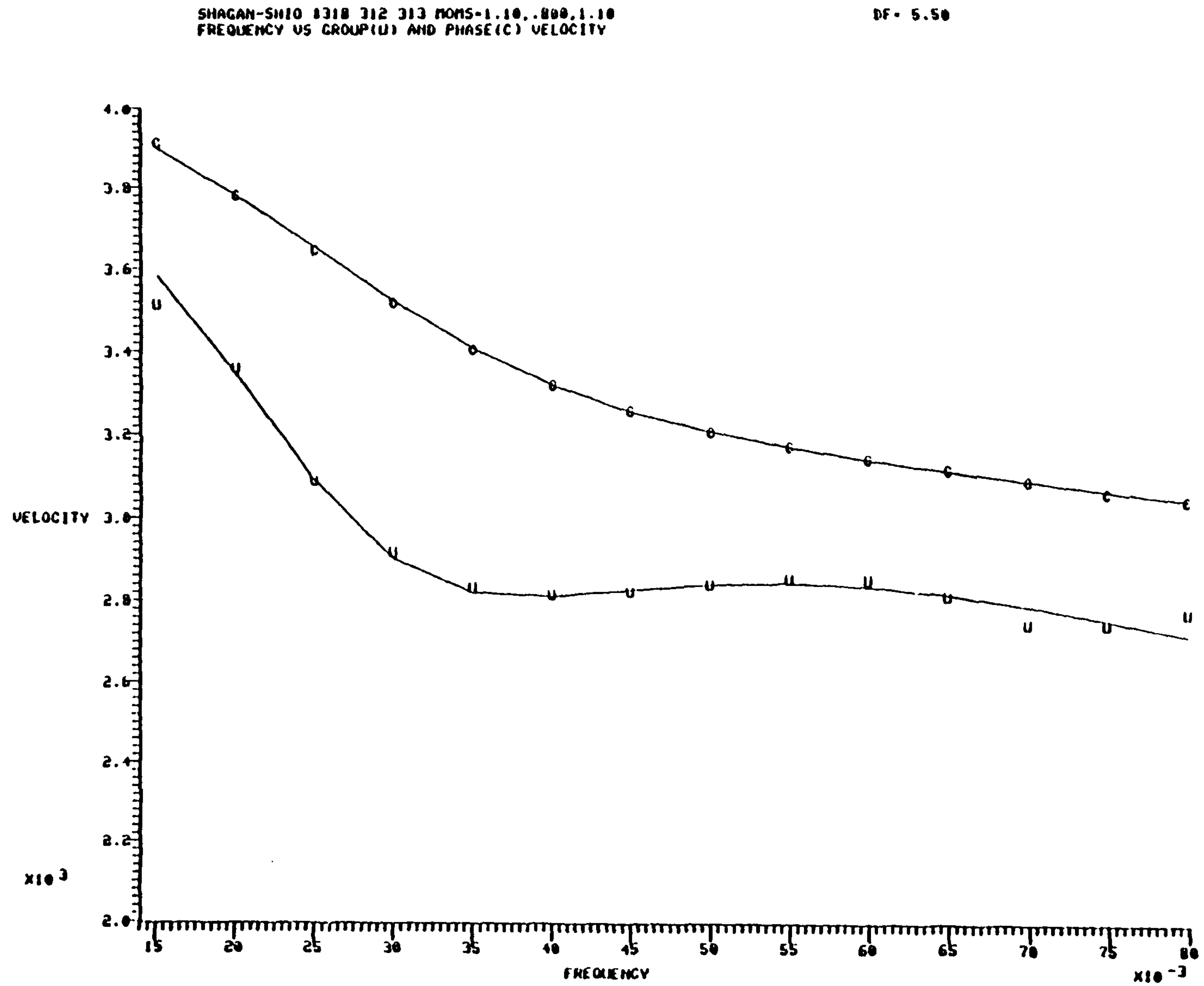

SHAGAN-SHIO 8318 312 313 MOMS-1.10,.800,1.10
DF- 5.50
FREQUENCY VS GROUP(U) AND PHASE(C) VELOCITY
VELOCITY
x10 3
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
15
20
25
30
35
40
45
50
55
60
65
70
75
80
FREQUENCY
x10 -3

Figure 16.2.

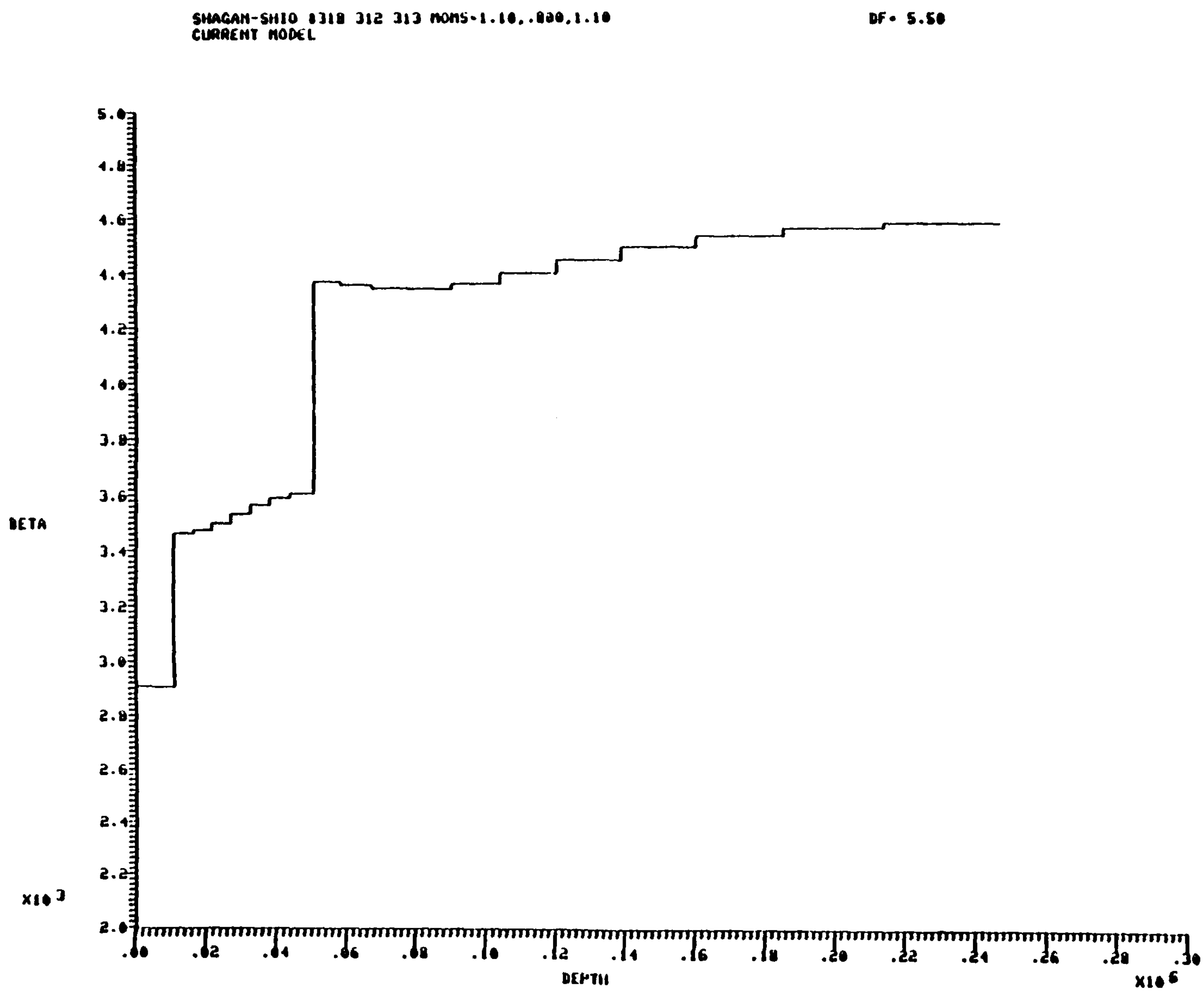

SHAGAN-SHIO 8318 312 313 MOMS-1.10,.800,1.10
CURRENT MODEL
DF= 5.50
BETA
X10 3
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30
DEPTH
X10 6

Figure 16.3.

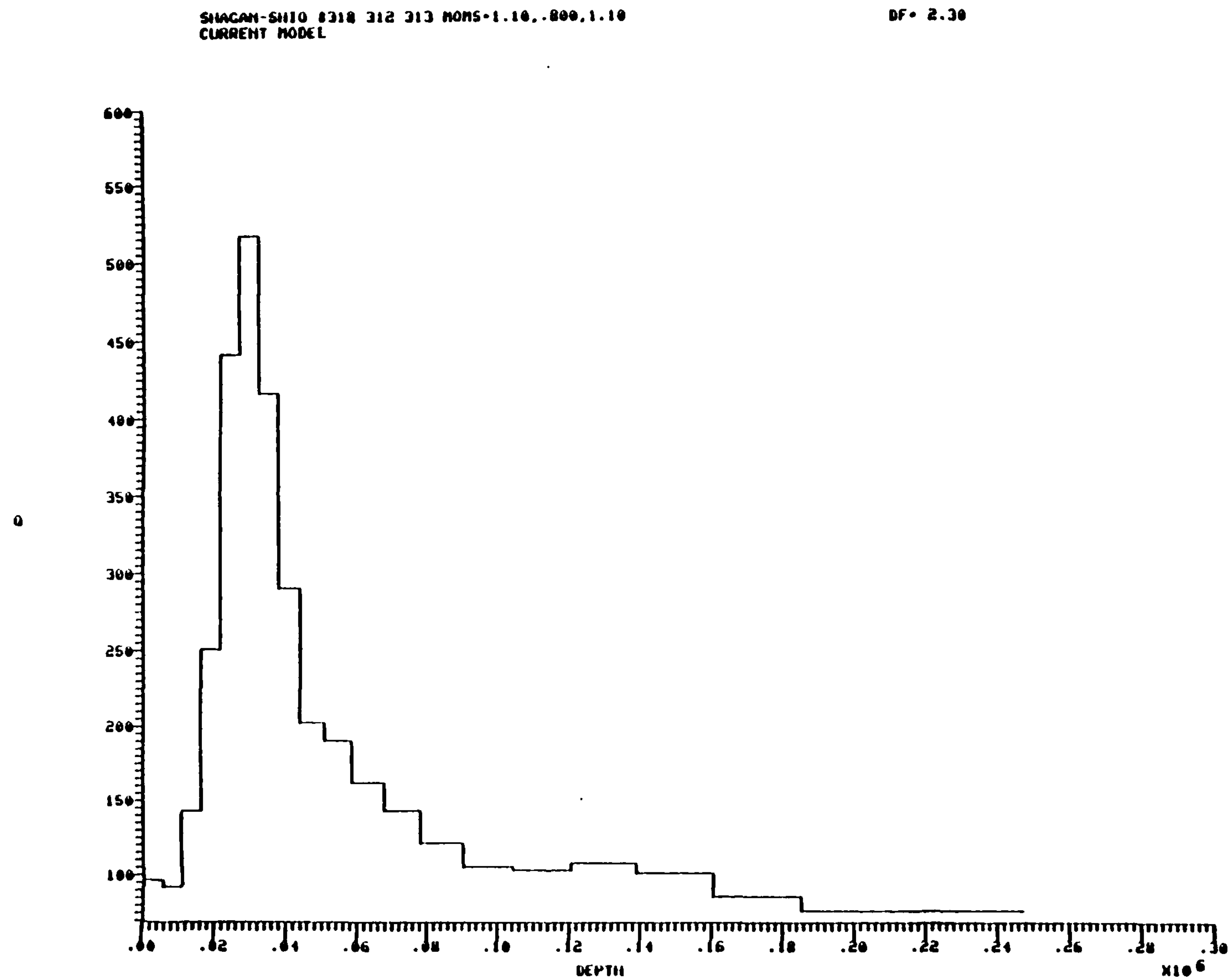

SHAGAN-SHIO 8318 312 313 MOMS-1.10,.800,1.10
CURRENT MODEL
DF= 2.30
Q
DEPTH
X10^6
600
550
500
450
400
350
300
250
200
150
100
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30

Figure 16.4

SHAGAN-SHIO STRUCTURE

I	DEPTH	THICK	ALPHA	BETA	RHO	QOM
1	5.434+003	5.433+003	5.179+003	2.307+003	2.290+003	3.654+001
2	1.087+004	5.433+003	5.175+003	2.305+003	2.298+003	9.221+001
3	1.630+004	5.433+003	6.171+003	3.464+003	2.652+003	1.422+002
4	2.174+004	5.433+003	6.131+003	3.475+003	2.659+003	2.511+002
5	2.717+004	5.433+003	6.237+003	3.501+003	2.675+003	4.413+002
6	3.260+004	5.433+003	6.296+003	3.534+003	2.697+003	5.170+002
7	3.304+004	5.433+003	6.353+003	3.566+003	2.718+003	4.151+002
8	4.393+004	5.394+003	6.399+003	3.592+003	2.735+003	2.906+002
9	5.074+004	6.507+003	6.425+003	3.607+003	2.745+003	2.026+002
10	5.360+004	7.862+003	7.732+003	4.363+003	3.239+003	1.906+002
11	6.760+004	9.090+003	7.764+003	4.356+003	3.233+003	1.627+002
12	7.317+004	1.048+004	7.741+003	4.345+003	3.224+003	1.435+002
13	9.028+004	1.211+004	7.737+003	4.343+003	3.223+003	1.218+002
14	1.043+005	1.399+004	7.769+003	4.361+003	3.235+003	1.053+002
15	1.204+005	1.615+004	7.337+003	4.399+003	3.259+003	1.037+002
16	1.391+005	1.866+004	7.924+003	4.448+003	3.291+003	1.083+002
17	1.606+005	2.155+004	8.010+003	4.496+003	3.322+003	1.018+002
18	5.074+004	2.489+004	2.083+003	4.537+003	3.349+003	5.640+001
19	2.143+005	2.875+004	8.133+003	4.565+003	3.367+003	7.708+001
20	2.475+005	3.320+004	8.167+003	4.584+003	3.380+003	7.703+001

Figure 16.5.

Figures 17.1 through 17.5 are on the following pages.

Figure 17. Path 3: SHAGAN–MAJO

Distance: 4911 km
Azimuth: 307°
Instrument: ASRO–LP
Events Processed: 318, 312, 313

Description: This is a good station. There is clear evidence of multipathing, but the separate arrivals are removed by the phase matched filter. The group velocities differ by 0.1 km/sec at 0.02 Hertz. Processing three seismograms and averaging helps to obtain consistent results.

SEC 8, OPTION(H-HELP) ? >1 L
GROUP VELS PICKED:

IDX	FREQ	GRPV	AMPL
1	.0105	3.980	.305
2	.0125	3.874	.470
3	.0141	3.807	.421
4	.0165	3.674	.342
5	.0189	3.552	.263
6	.0205	3.347	.117
7	.0257	3.335	.162
8	.0283	3.344	.291
9	.0303	3.318	.454
10	.0324	3.277	.618
11	.0343	3.240	.753
12	.0363	3.205	.844
13	.0385	3.170	.911
14	.0408	3.133	.970
15	.0427	3.102	1.000
16	.0443	3.086	.974
17	.0461	3.077	.912
18	.0484	3.068	.852
19	.0510	3.057	.816
20	.0540	3.045	.809
21	.0570	3.030	.830
22	.0597	3.016	.864
23	.0613	3.007	.882
24	.0625	3.003	.864
25	.0637	3.002	.813
26	.0649	3.002	.740
27	.0661	3.002	.656
28	.0673	3.001	.566
29	.0682	3.000	.478
30	.0692	2.998	.394
31	.0703	2.993	.320
32	.0722	2.987	.258
33	.0752	2.981	.212
34	.0779	2.976	.178
35	.0808	2.972	.153
36	.0837	2.969	.133
37	.0855	2.967	.117
38	.0876	2.966	.103
39	.0888	2.966	.089
40	.0898	2.967	.077

SEC 8, OPTION(H-HELP) ? >

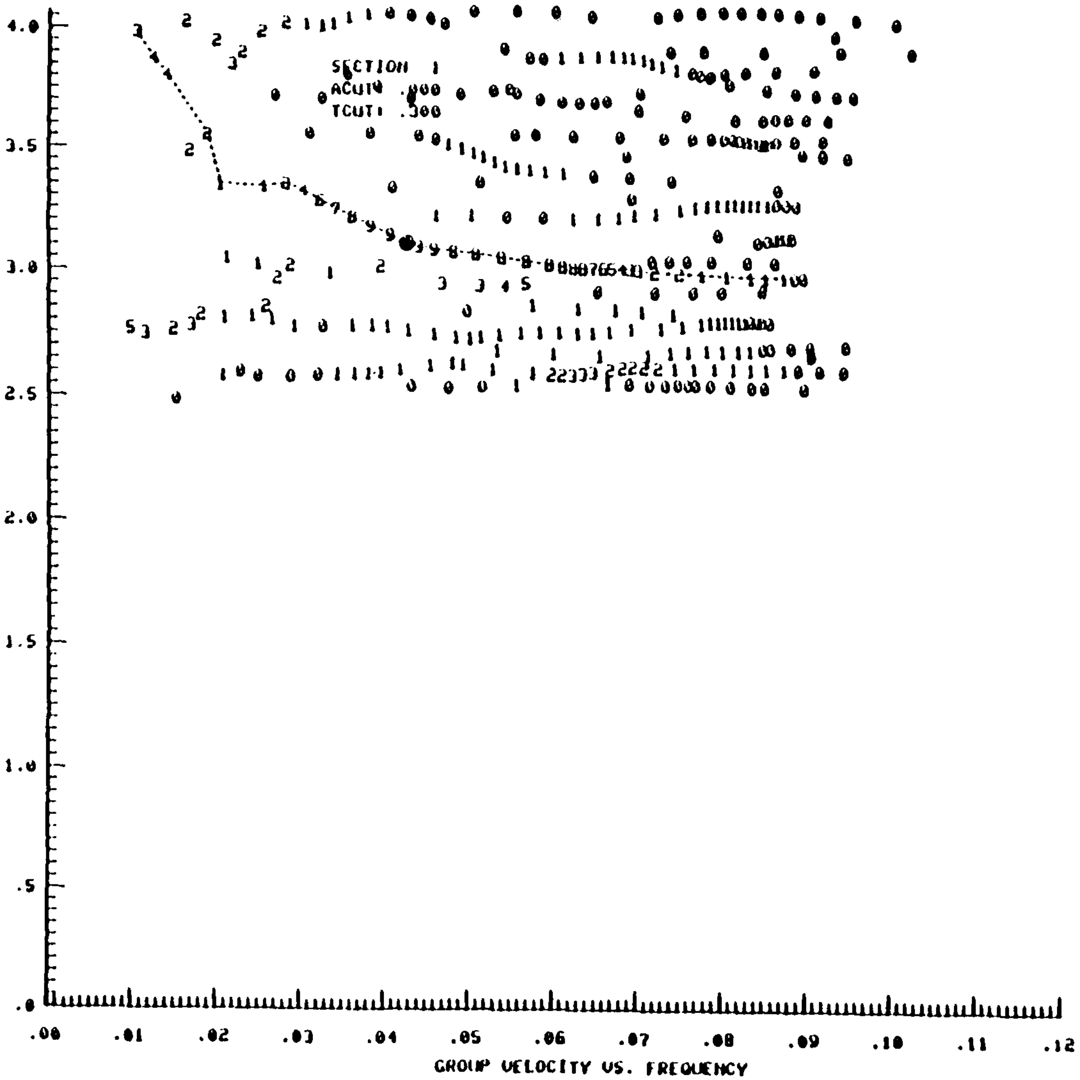


Figure 17.1.

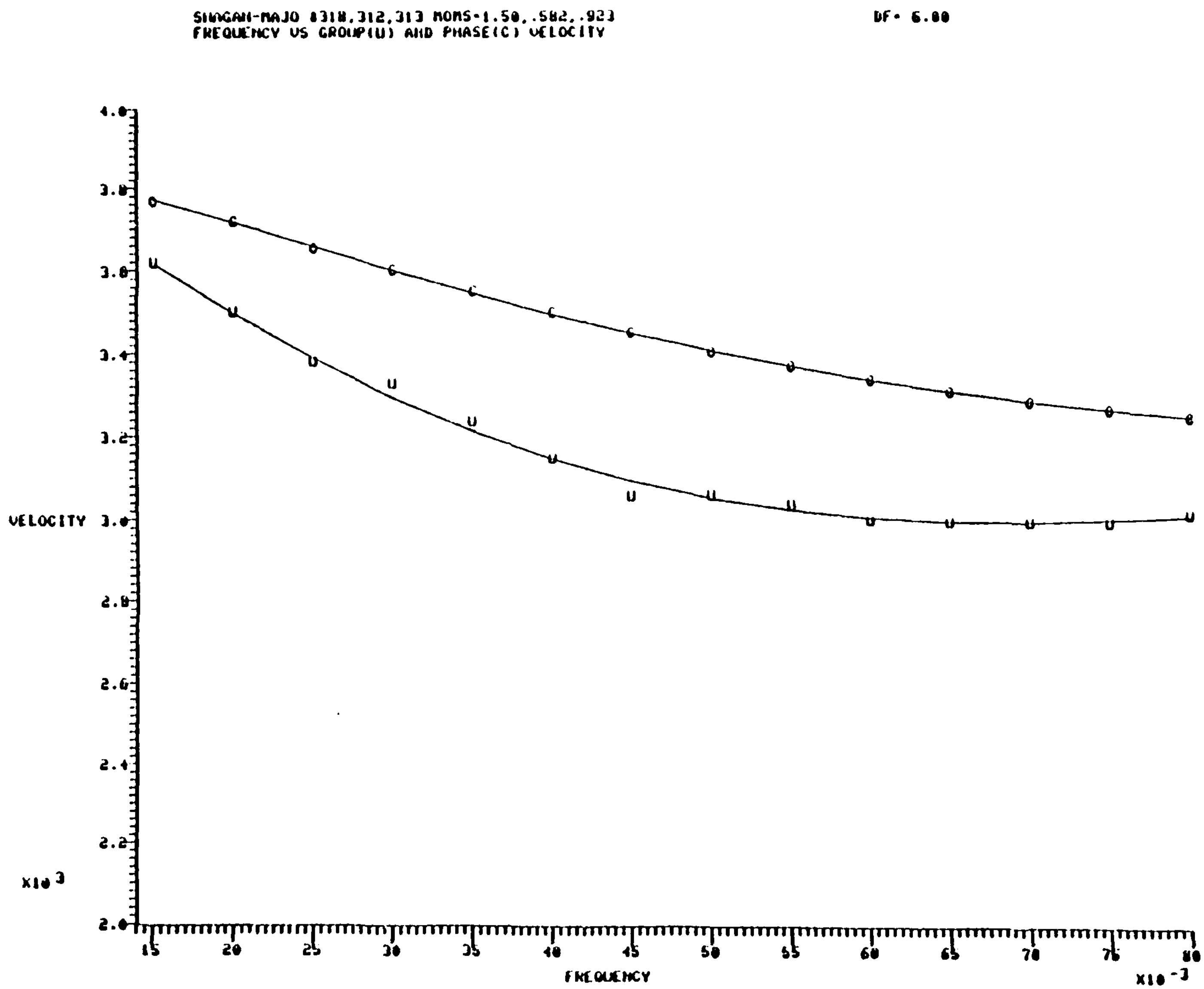

SHAGAN-MAJO #310,312,313 MOMS=1.50,.582,.923
DF= 6.00
FREQUENCY VS GROUP(U) AND PHASE(C) VELOCITY
VELOCITY
x10^3
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
15
20
25
30
35
40
45
50
55
60
65
70
75
80
FREQUENCY
x10^-3

Figure 17.2.

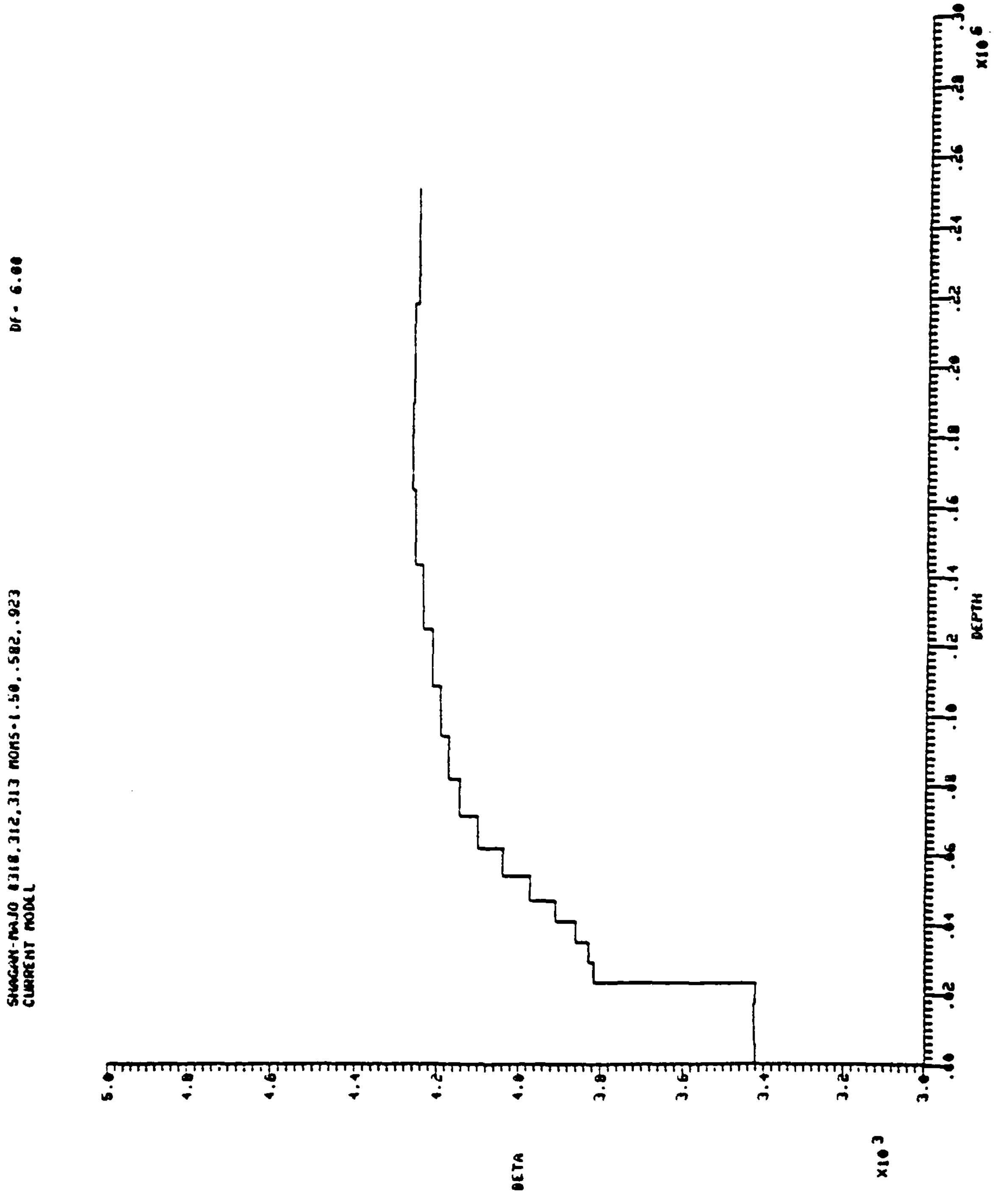

SHAGAN-MAJO 6318,312,313 MOMS-1.50,.582,.923
CURRENT MODEL
DF- 6.00
BETA
X10 3
DEPTH
X10 6

Figure 17.3.

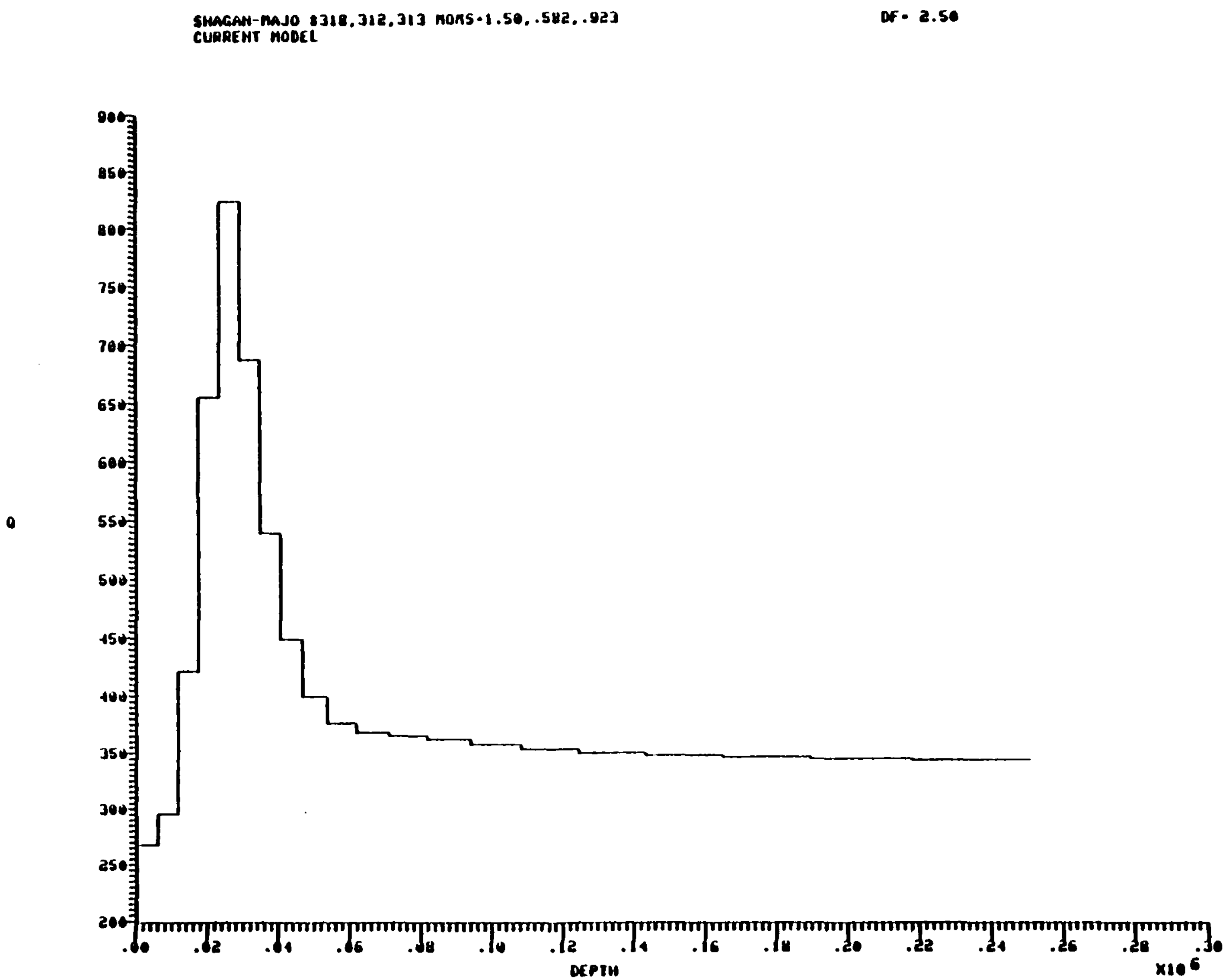

SHAGAN-MAJO 8318,312,313 MOMS-1.50,.582,.923
CURRENT MODEL
DF- 2.50
Q
DEPTH
X10 6
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30

Figure 17.4

SHAGAN-MAJO STRUCTURE

I	DEPTH	THICK	ALPHA	BETA	RHO	QOM
1	5.800+003	5.799+003	6.095+003	3.421+003	2.624+003	2.674+002
2	1.160+004	5.799+003	6.098+003	3.423+003	2.625+003	2.953+002
3	1.740+004	5.799+003	6.098+003	3.423+003	2.625+003	4.214+002
4	2.320+004	5.799+003	6.093+003	3.420+003	2.623+003	6.554+002
5	2.900+004	5.799+003	6.798+003	3.816+003	2.880+003	9.236+002
6	3.480+004	5.799+003	6.823+003	3.830+003	2.899+003	6.373+002
7	4.060+004	5.799+003	6.379+003	3.861+003	2.910+003	5.390+002
8	4.671+004	6.107+003	6.964+003	3.909+003	2.941+003	4.468+002
9	5.373+004	7.025+003	7.075+003	3.971+003	2.981+003	3.995+002
10	6.182+004	8.082+003	7.197+003	4.040+003	3.026+003	3.764+002
11	7.111+004	9.298+003	7.306+003	4.101+003	3.066+003	3.682+002
12	3.181+004	1.069+004	7.385+003	4.145+003	3.094+003	3.654+002
13	9.412+004	1.230+004	7.434+003	4.173+003	3.112+003	3.625+002
14	1.083+005	1.415+004	7.468+003	4.192+003	3.125+003	3.580+002
15	1.246+005	1.623+004	7.506+003	4.213+003	3.138+003	3.536+002
16	1.433+005	1.873+004	7.548+003	4.237+003	3.154+003	3.504+002
17	1.648+005	2.155+004	7.580+003	4.255+003	3.166+003	3.491+002
18	1.596+005	2.479+004	7.595+003	4.263+003	3.171+003	3.464+002
19	2.182+005	2.852+004	7.589+003	4.260+003	3.169+003	3.448+002
20	2.510+005	3.281+004	7.572+003	4.250+003	3.162+003	3.435+002

Figure 17.5.

Figures 18.1 through 18.5 are on the following pages.

Figure 18. Path 4: SHAGAN–GRFO

Distance: 4699 km
Azimuth: 62.7°
Instrument: SRO–LP
Events Processed: 318, 312

Description: This is a good, although somewhat noisy, station. The group velocity plot shows many distinct arrivals, but the phase matched filter seems to separate them well. The final phase and group velocities are quite consistent for the two events processed.

```
SEC 0, OPTION(H-HELP) ? )L
SEC 0, OPTION(H-HELP) ? )1 L
 GROUP VELS PICKED:
IDX  FREQ  GRPV  AMPL

  1  .0000   .000  .093
  2  .0000   .000  .000
  3  .0144  3.933  .150
  4  .0173  3.877  .156
  5  .0200  3.767  .219
  6  .0226  3.631  .311
  7  .0249  3.511  .430
  8  .0272  3.421  .552
  9  .0296  3.331  .680
 10  .0319  3.236  .809
 11  .0341  3.167  .934
 12  .0359  3.120 1.000
 13  .0377  3.081  .991
 14  .0397  3.051  .947
 15  .0420  3.031  .903
 16  .0444  3.016  .875
 17  .0472  3.001  .869
 18  .0496  2.988  .876
 19  .0517  2.977  .881
 20  .0535  2.971  .866
 21  .0553  2.969  .831
 22  .0572  2.968  .785
 23  .0593  2.968  .737
 24  .0614  2.968  .689
 25  .0632  2.968  .637
 26  .0647  2.967  .577
 27  .0658  2.967  .508
 28  .0664  2.966  .430
 29  .0669  2.956  .347
 30  .0707  2.935  .287
 31  .0742  2.924  .248
 32  .0766  2.917  .218
 33  .0781  2.912  .192
 34  .0794  2.909  .166
 35  .0804  2.907  .142
 36  .0816  2.906  .120
 37  .0827  2.905  .101
 38  .0839  2.905  .084
 39  .0849  2.905  .069
 40  .0858  2.906  .057
SEC 0, OPTION(H-HELP) ? >
```

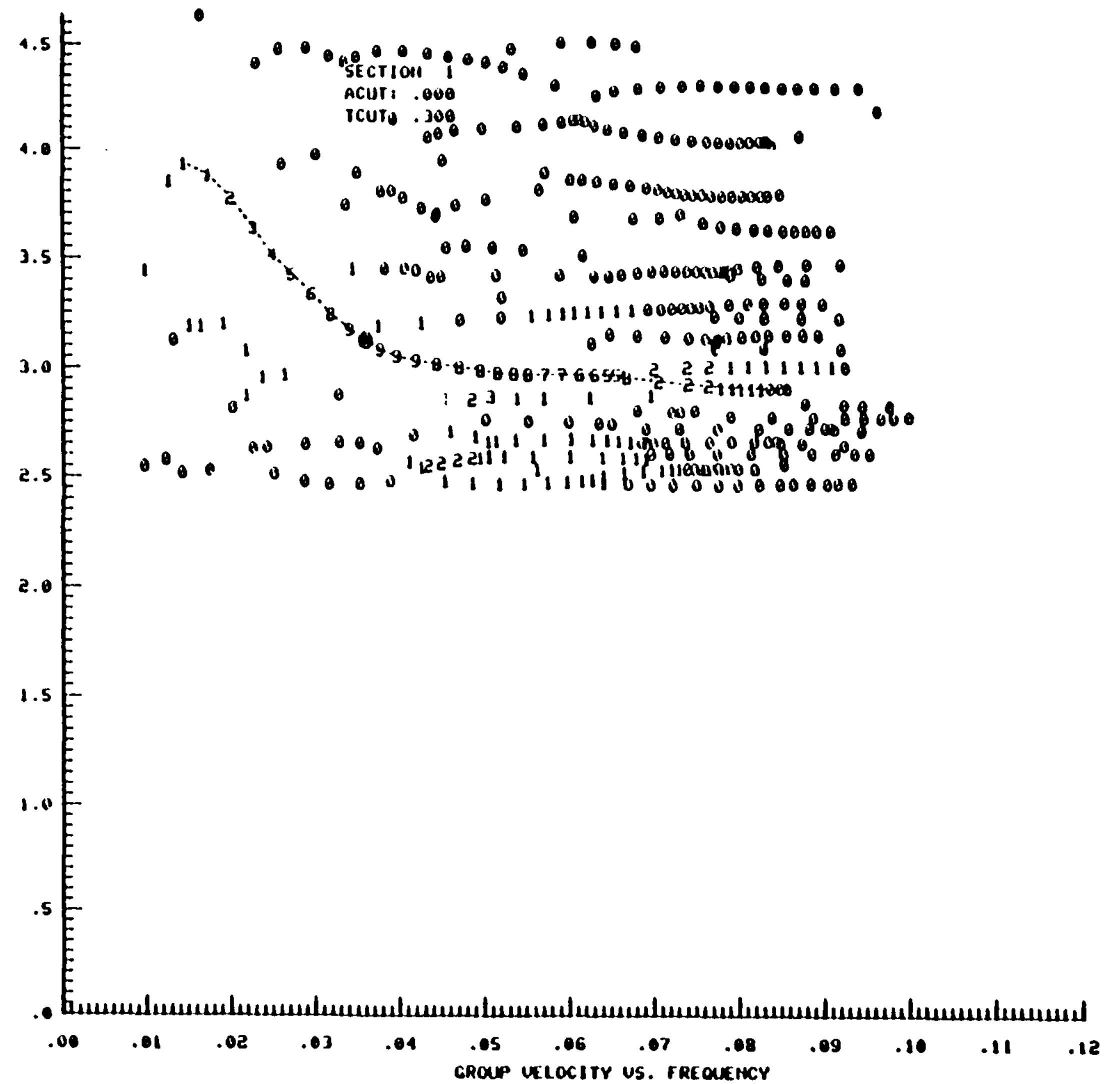
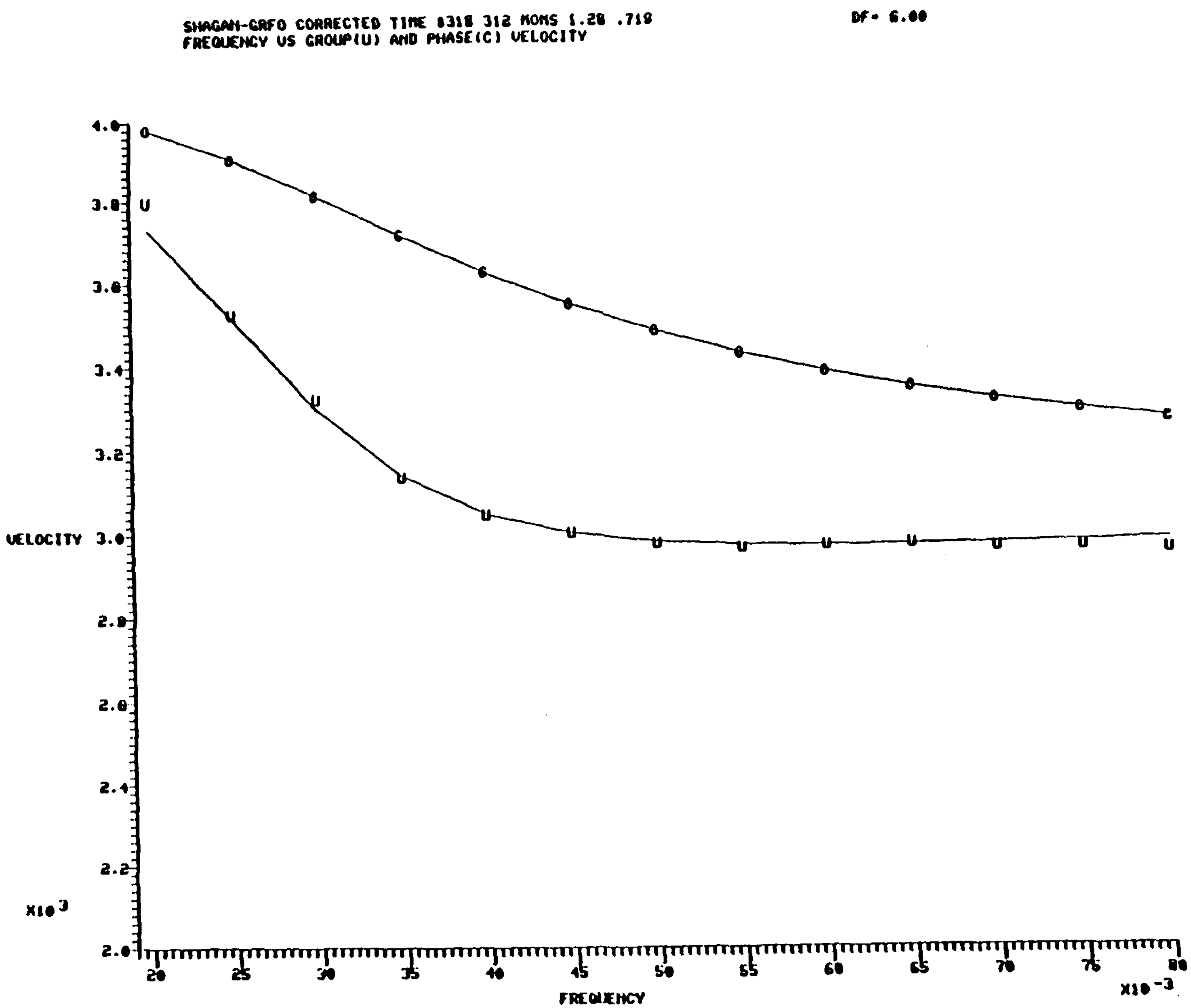
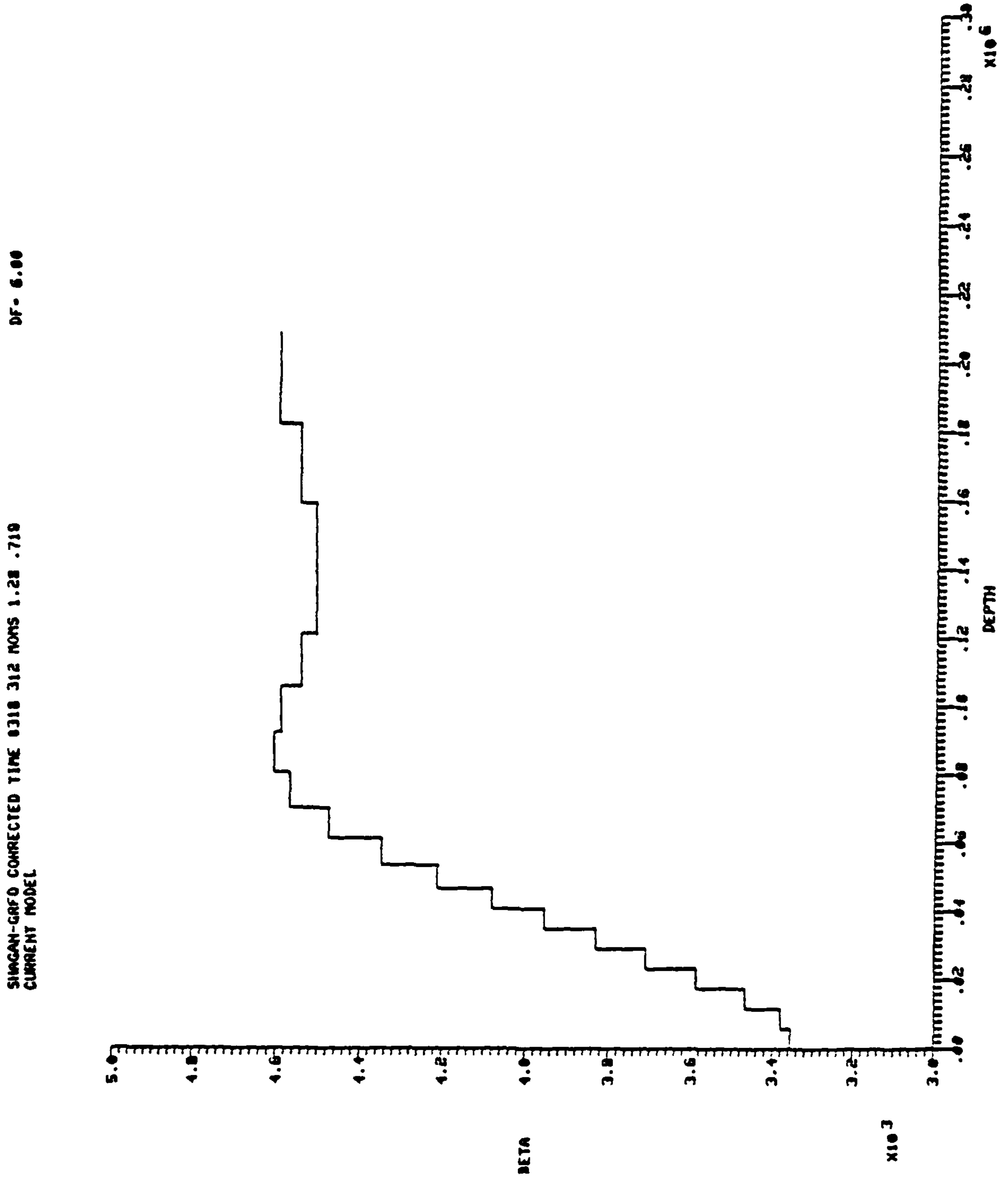


Figure 18.1.



SHAGAN-GRFO CORRECTED TIME 8318 312 MOMS 1.28 .718
FREQUENCY VS GROUP(U) AND PHASE(C) VELOCITY
DF= 6.00
VELOCITY
X10 3
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
20
25
30
35
40
45
50
55
60
65
70
75
80
FREQUENCY
X10 -3

Figure 18.2.



SMAGAN-GRFO CORRECTED TIME 0318 312 MOMS 1.28 .719
CURRENT MODEL
DF- 6.00
BETA
X10 3
DEPTH
X10 6

Figure 18.3.

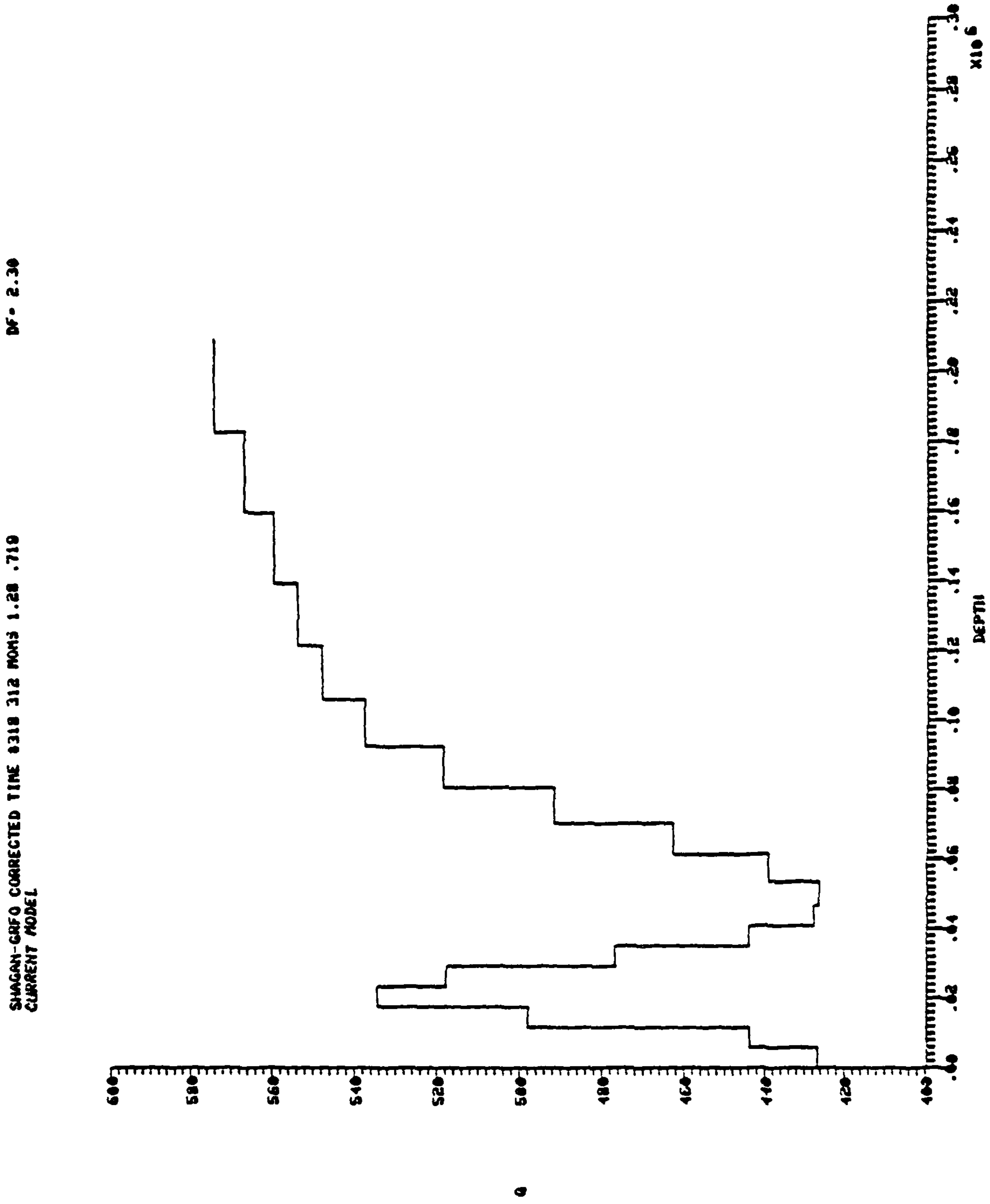

SHAGAN-GRFO CORRECTED TIME 0310 312 MOMS 1.28 .719
CURRENT MODEL
DF= 2.30
Q
DEPTH
X10^6

Figure 18.4

SHAGAN-GRFO STRUCTURE

I	DEPTH	THICK	ALPHA	BETA	RHO	QQA
1	5.834+003	5.833+003	5.377+003	3.355+003	2.581+003	4.270+002
2	1.167+004	5.833+003	6.020+003	3.379+003	2.596+003	4.441+002
3	1.750+004	5.833+003	6.177+003	3.467+003	2.654+003	4.981+002
4	2.334+004	5.833+003	6.390+003	3.587+003	2.732+003	5.346+002
5	2.917+004	5.833+003	6.610+003	3.710+003	2.811+003	5.178+002
6	3.500+004	5.833+003	6.827+003	3.832+003	2.891+003	4.770+002
7	4.084+004	5.833+003	7.044+003	3.954+003	2.970+003	4.441+002
8	4.679+004	5.949+003	7.267+003	4.079+003	3.051+003	4.279+002
9	5.360+004	6.815+003	7.502+003	4.211+003	3.137+003	4.266+002
10	6.141+004	7.808+003	7.748+003	4.349+003	3.227+003	4.393+002
11	7.036+004	8.946+003	7.972+003	4.475+003	3.309+003	4.629+002
12	8.061+004	1.024+004	8.136+003	4.567+003	3.369+003	4.917+002
13	9.235+004	1.174+004	8.204+003	4.605+003	3.393+003	5.184+002
14	1.058+005	1.345+004	8.172+003	4.587+003	3.382+003	5.373+002
15	1.212+005	1.541+004	8.086+003	4.539+003	3.350+003	5.476+002
16	1.389+005	1.765+004	8.022+003	4.503+003	3.327+003	5.535+002
17	1.591+005	2.023+004	8.024+003	4.504+003	3.323+003	5.592+002
18	1.823+005	2.317+004	8.092+003	4.542+003	3.352+003	5.665+002
19	2.088+005	2.655+004	8.183+003	4.593+003	3.385+003	5.739+002

Figure 18.5.

Figures 19.1 through 19.5 are on the following pages.

Figure 19. Path 5: SHAGAN-ANTO

Distance: 3740 km
Azimuth: 57.2°
Instrument: SRO-LP
Events Processed: 318, 312

Description: This is a difficult, noisy station to process. There are numerous multiple arrivals on the group velocity plots. No group velocity curve could be found for Event 313. Nevertheless, fairly consistent velocities were obtained for the remaining two events from 0.02 to 0.07 Hertz, and when inverted, they produce a reasonable velocity and Q structure.

SEC 8, OPTION(H=HELP) ? >
>1 L
GROUP VELS PICKED:

IDX	FREQ	GRPV	AMPL
1	.0000	.000	.000
2	.0000	.000	.000
3	.0163	3.827	.211
4	.0201	3.679	.331
5	.0232	3.587	.465
6	.0271	3.421	.692
7	.0295	3.260	.993
8	.0313	3.177	.987
9	.0336	3.093	.779
10	.0374	3.020	.657
11	.0396	2.978	.569
12	.0444	2.748	1.000
13	.0461	2.755	.916
14	.0488	2.761	.799
15	.0516	2.759	.701
16	.0542	2.752	.603
17	.0567	2.737	.503
18	.0608	2.708	.421
19	.0631	2.664	.380
20	.0641	2.668	.310
21	.0654	2.668	.241
22	.0668	2.666	.180
23	.0683	2.663	.132
24	.0699	2.659	.095
25	.0716	2.654	.067
26	.0742	2.647	.048
27	.0763	2.640	.034
28	.0800	2.632	.025
29	.0838	2.623	.019
30	.0926	2.589	.016

SEC 8, OPTION(H=HELP) ? >

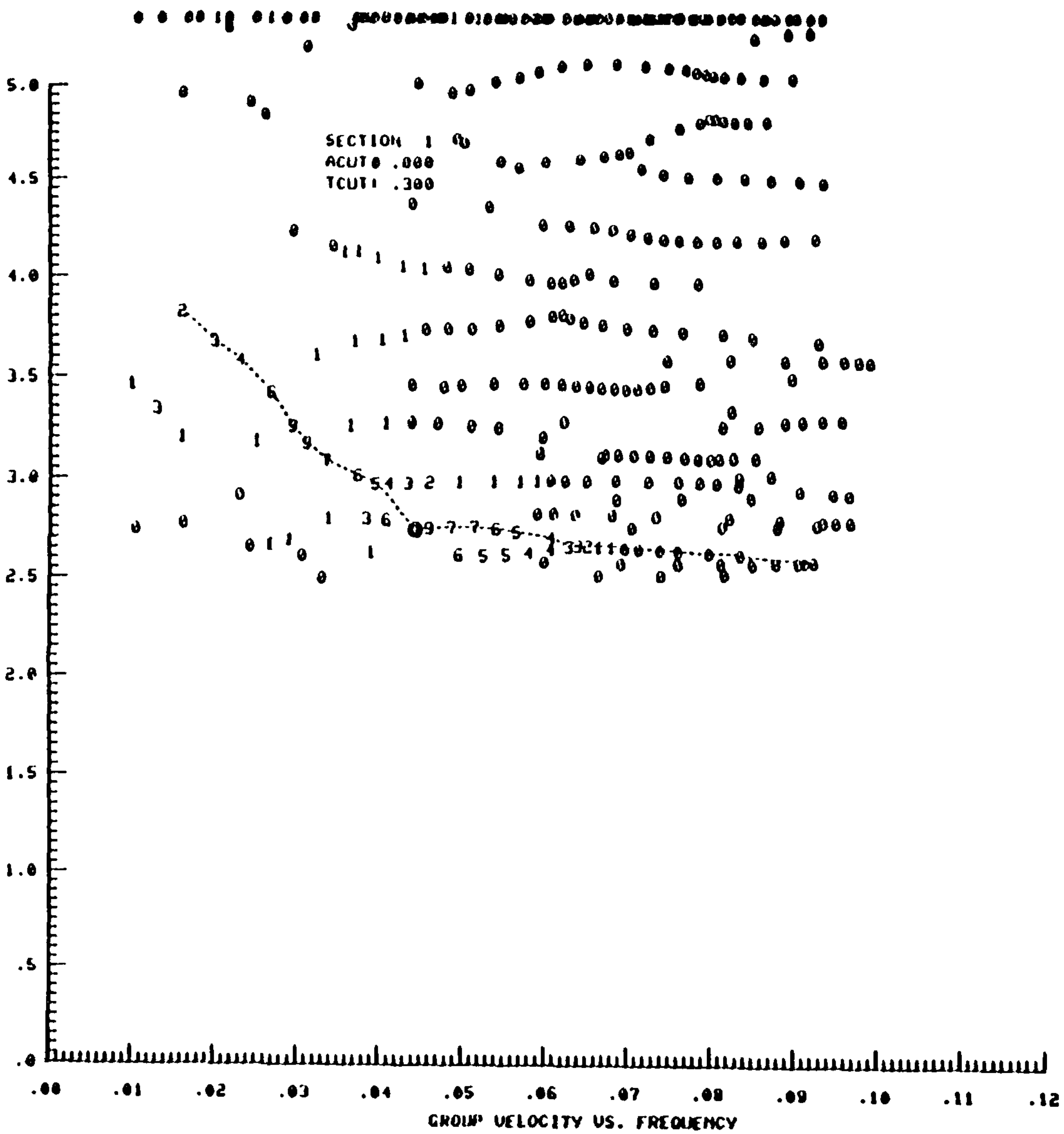


Figure 19.1.

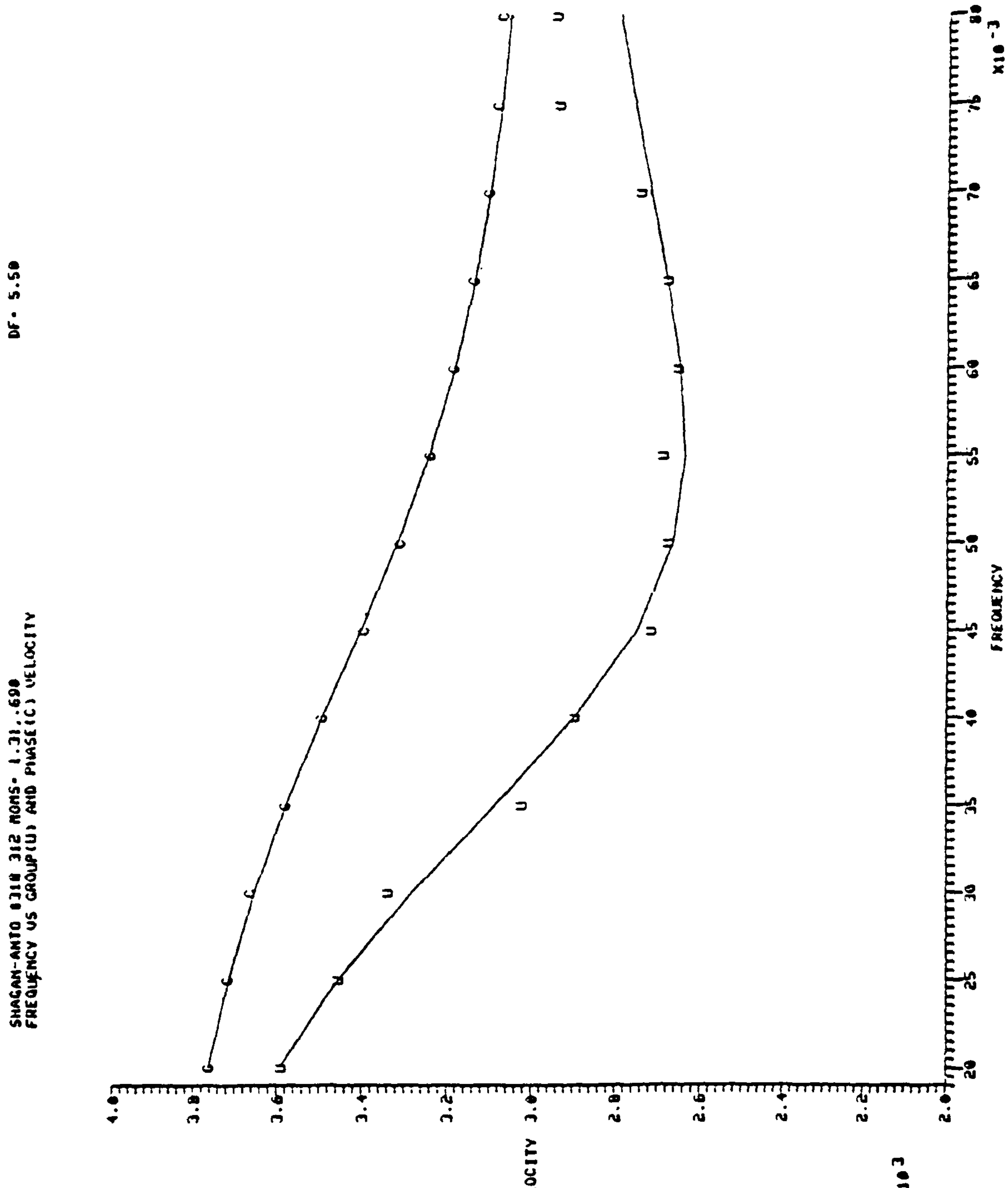

FREQUENCY VS GROUP(U) AND PHASE(C) VELOCITY
DF= 5.50
VELOCITY
FREQUENCY

Figure 19.2.

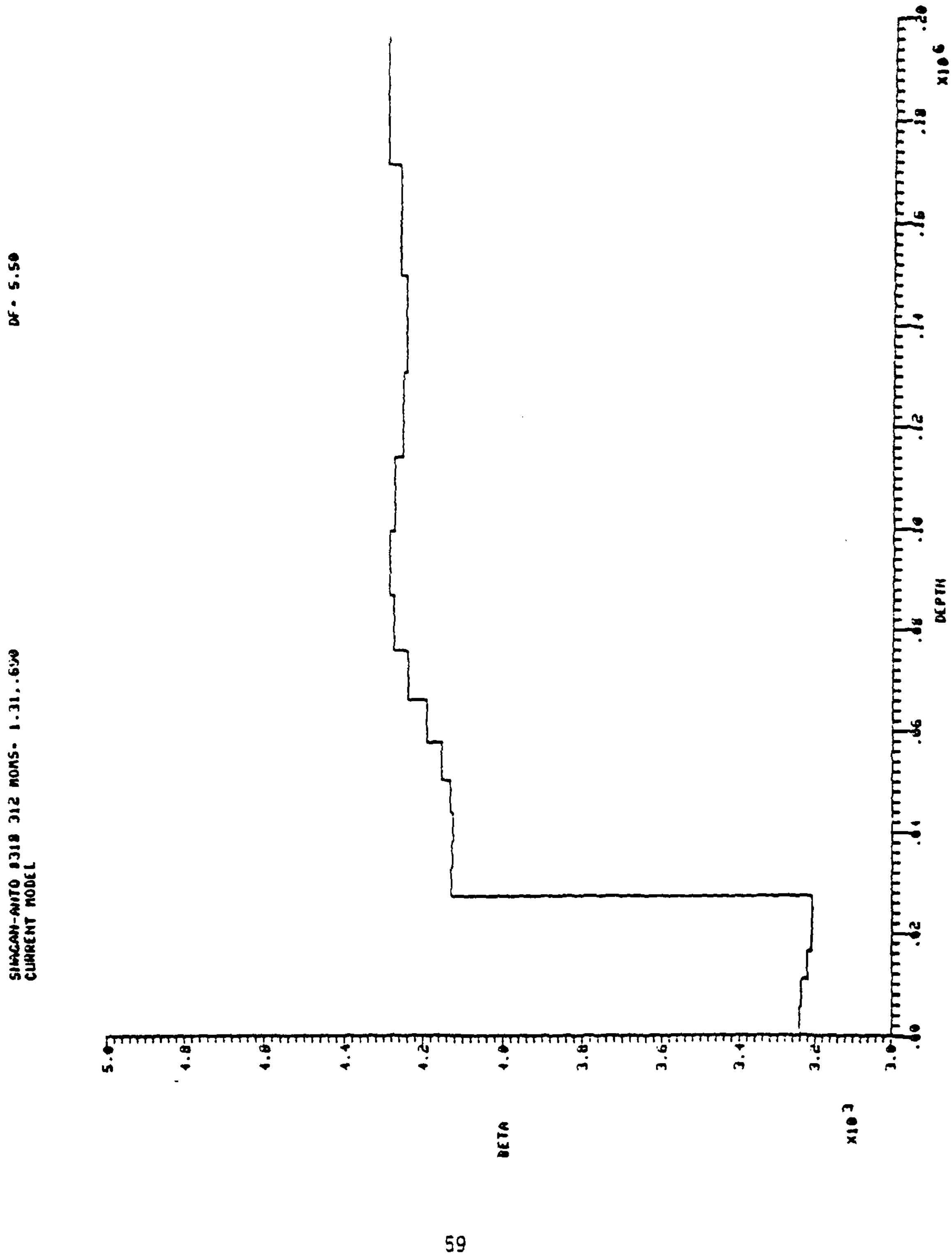

CURRENT MODEL
DF= 5.50
BETA
x10 3
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
DEPTH
x10 6
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20

Figure 19.3.

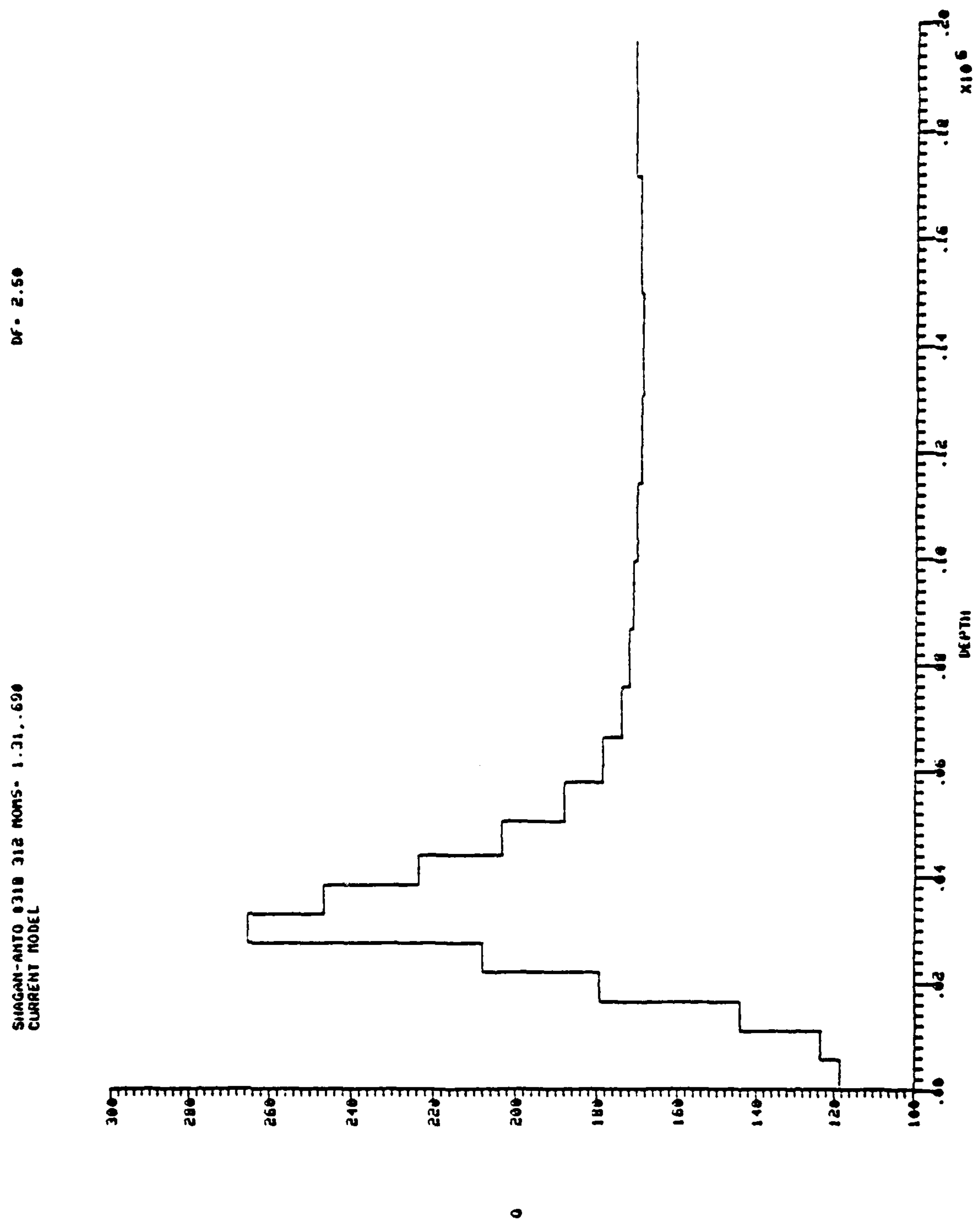

SHAGAN-ANTO 0318 318 MOMS- 1.31,.690
CURRENT MODEL
DF- 2.50
300
280
260
240
220
200
180
160
140
120
100
Q
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
DEPTH
X10^6

Figure 19.4

SHAGAN-ANTO STRUCTURE

I	DEPTH	THICK	ALPHA	BETA	RHO	QSM
1	5.480+003	5.480+003	5.772+003	3.240+003	2.506+003	1.155+002
2	1.096+004	5.480+003	5.765+003	3.236+003	2.503+003	1.236+002
3	1.644+004	5.480+003	5.735+003	3.219+003	2.492+003	1.443+002
4	2.192+004	5.480+003	5.715+003	3.208+003	2.485+003	1.734+002
5	2.740+004	5.480+003	5.713+003	3.207+003	2.485+003	2.250+002
6	3.288+004	5.480+003	7.356+003	4.125+003	3.084+003	2.652+002
7	3.836+004	5.480+003	7.351+003	4.125+003	3.082+003	2.465+002
8	4.396+004	5.600+003	7.347+003	4.124+003	3.081+003	2.237+002
9	5.038+004	6.418+003	7.358+003	4.130+003	3.084+003	2.033+002
10	5.774+004	7.355+003	7.395+003	4.151+003	3.098+003	1.930+002
11	6.617+004	8.429+003	7.465+003	4.190+003	3.123+003	1.787+002
12	7.583+004	9.660+003	7.548+003	4.237+003	3.154+003	1.741+002
13	8.690+004	1.107+004	7.613+003	4.273+003	3.177+003	1.722+002
14	9.955+004	1.268+004	7.634+003	4.285+003	3.195+003	1.712+002
15	1.141+005	1.453+004	7.611+003	4.272+003	3.177+003	1.702+002
16	1.308+005	1.666+004	7.572+003	4.250+003	3.162+003	1.692+002
17	1.499+005	1.909+004	7.557+003	4.242+003	3.157+003	1.688+002
18	1.718+005	2.188+004	7.584+003	4.257+003	3.167+003	1.593+002
19	1.968+005	2.507+004	7.639+003	4.288+003	3.137+003	1.705+002

Figure 19.5.

Figure 20.1 through 20.5 are on the following pages.

Figure 20. Path 6: SHAGAN-CHTO

Distance: 3890 km
Azimuth: 337.1°
Instrument: SRO-LP
Events Processed: 318, 312, 313

Description: This is a rather noisy station with multiple arrivals and multipathing present. Most difficult is a branch in the group velocity curve above 0.06 Hertz. This causes the group velocity from the phase matched filer to jump to the other branches. Averaging velocities for three events helped to obtain a consistent result.

SEC 0, OPTION(H=HELP) ?)1 L
GROUP VELS PICKED:

IDX	FREQ	GRPV	AMPL
1	.0105	3.559	.141
2	.0153	3.507	.422
3	.0199	3.393	.723
4	.0246	3.149	.839
5	.0293	3.034	1.000
6	.0333	2.970	.948
7	.0370	2.911	.747
8	.0403	2.924	.453
9	.0492	2.920	.412
10	.0568	2.894	.643
11	.0597	2.871	.919
12	.0613	2.871	.938
13	.0626	2.872	.739
14	.0632	2.876	.474
15	.0643	2.849	.262
16	.0664	2.843	.141
17	.0711	2.846	.079
18	.0788	2.848	.052
19	.0870	2.848	.039
20	.0924	2.851	.031

SEC 0, OPTION(H=HELP) ?)

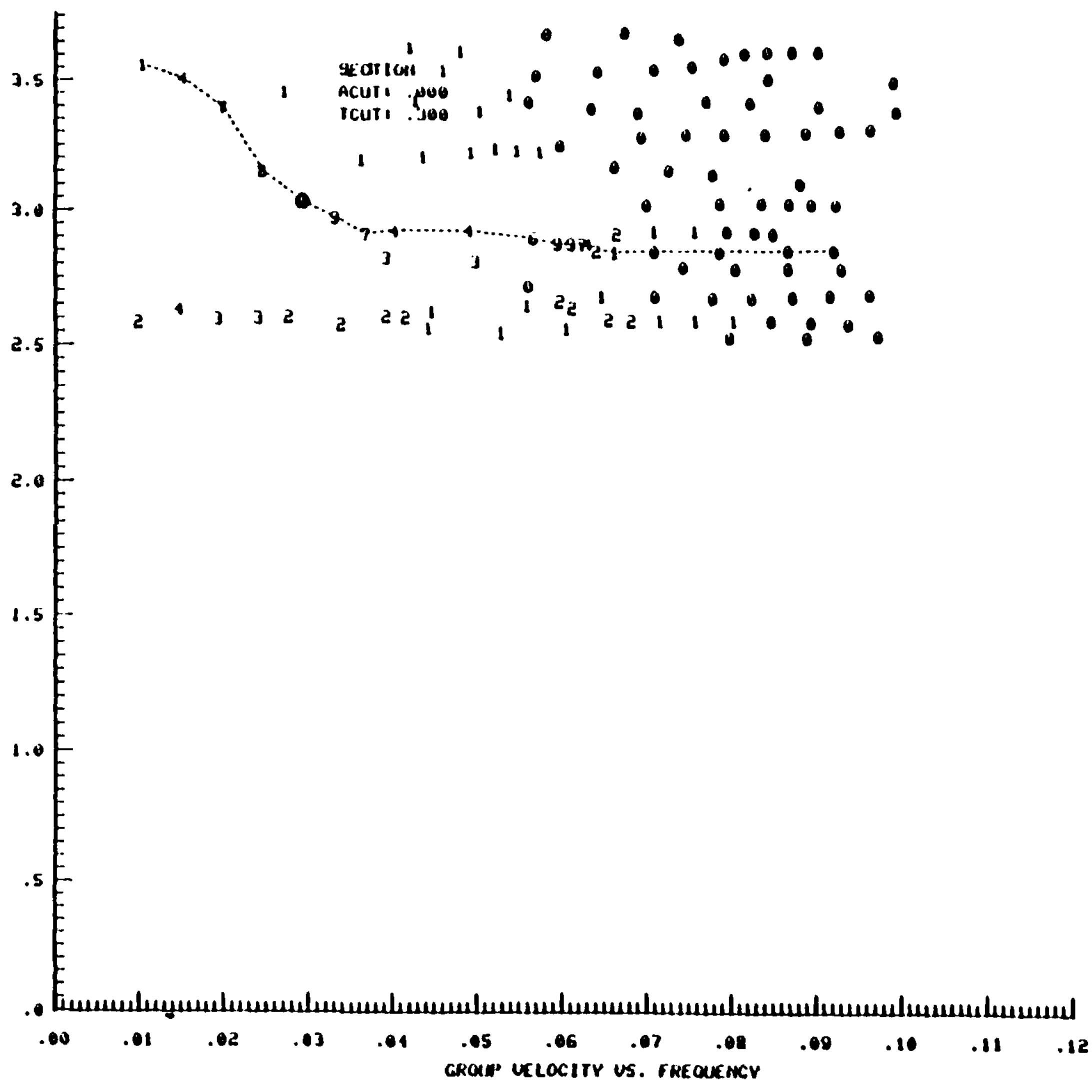


Figure 20.1.

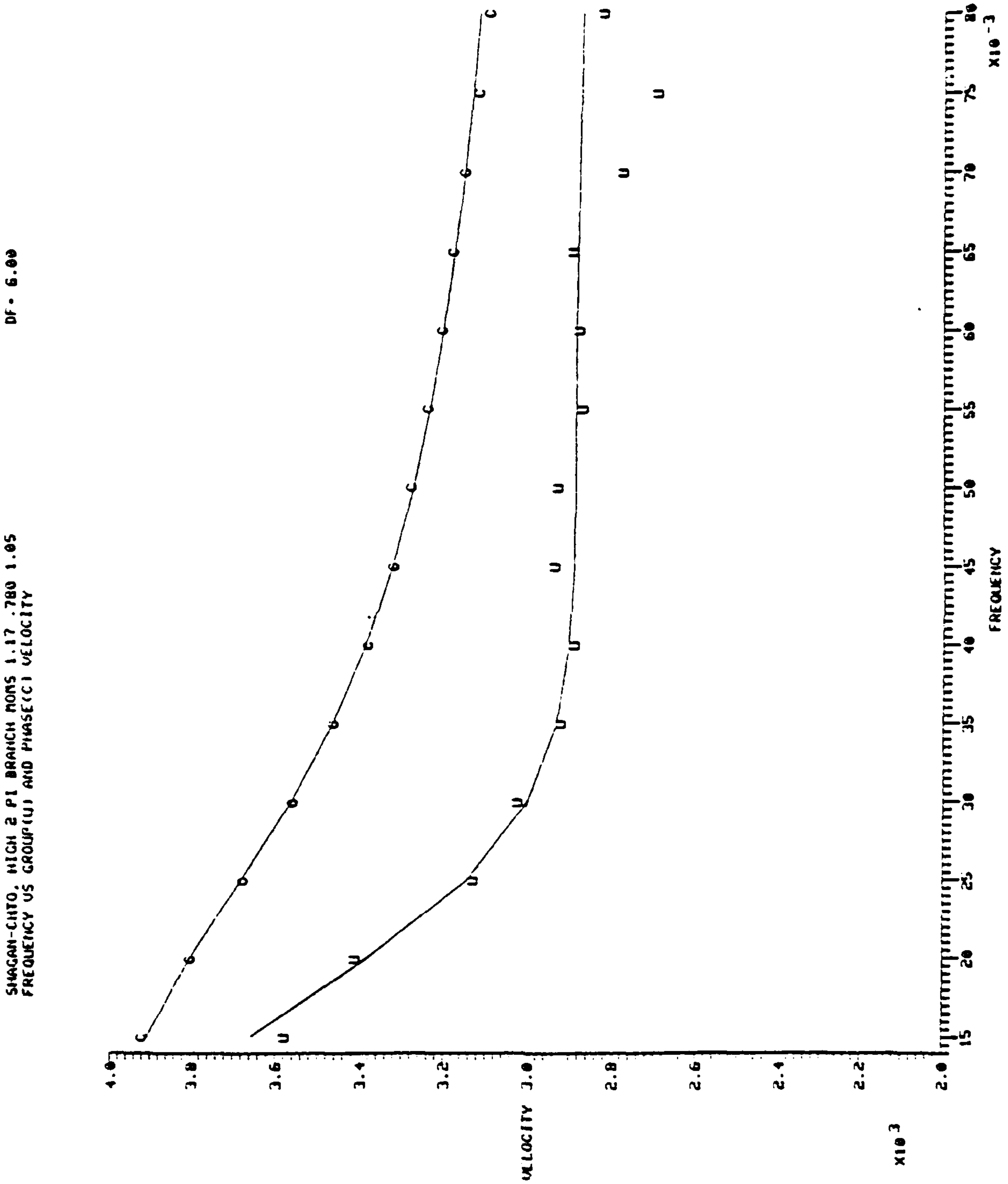

SHAGAN-CHTO, HIGH 2 PI BRANCH MOMS 1.17 .780 1.05
FREQUENCY VS GROUP(U) AND PHASE(C) VELOCITY
DF = 6.00
VELOCITY
x10 3
FREQUENCY
x10 -3

Figure 20.2.

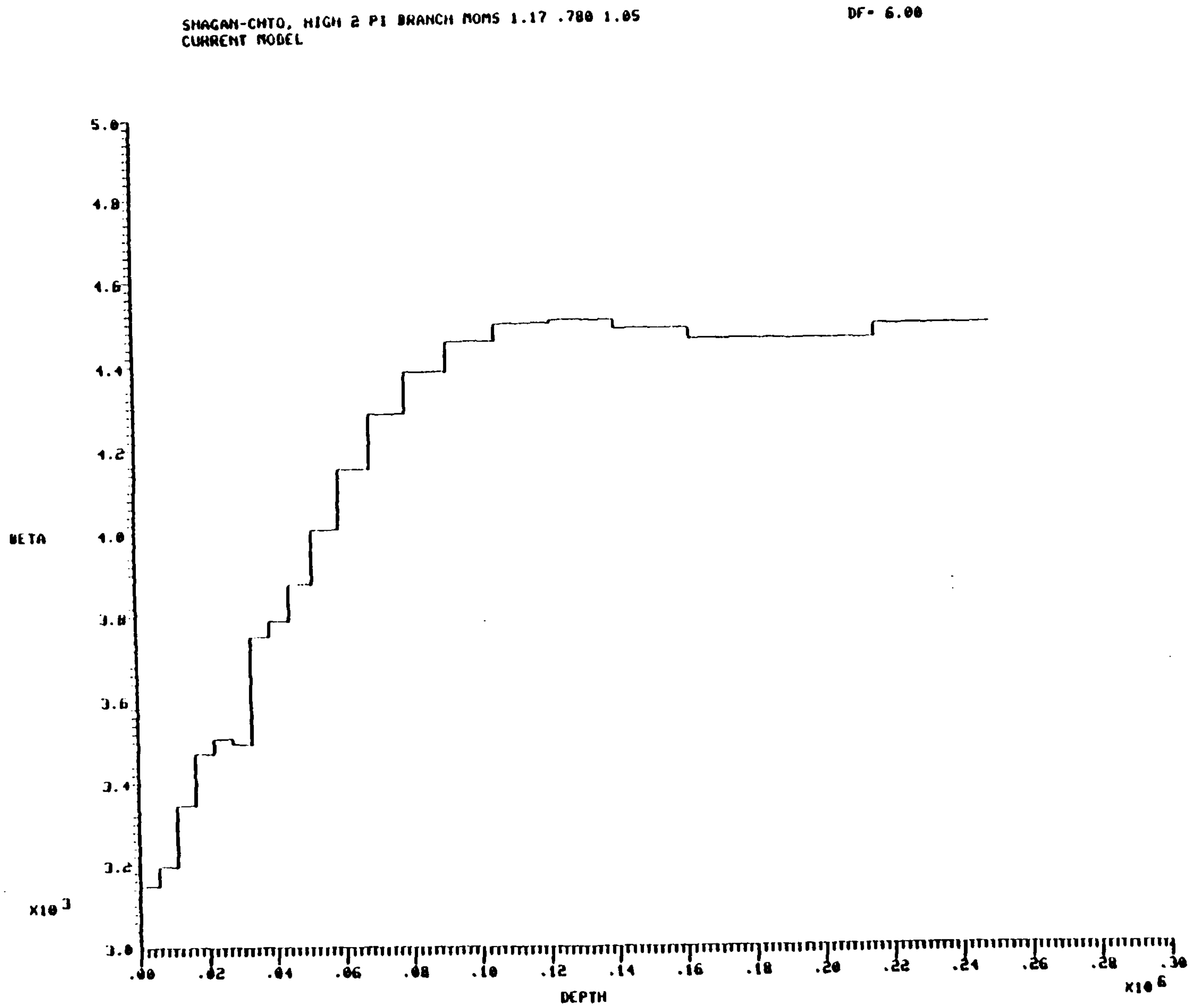

SHAGAN-CHTO, HIGH 2 PI BRANCH MOMS 1.17 .780 1.05
CURRENT MODEL
DF= 6.00
BETA
X10 3
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30
X10 6
DEPTH

Figure 20.3.

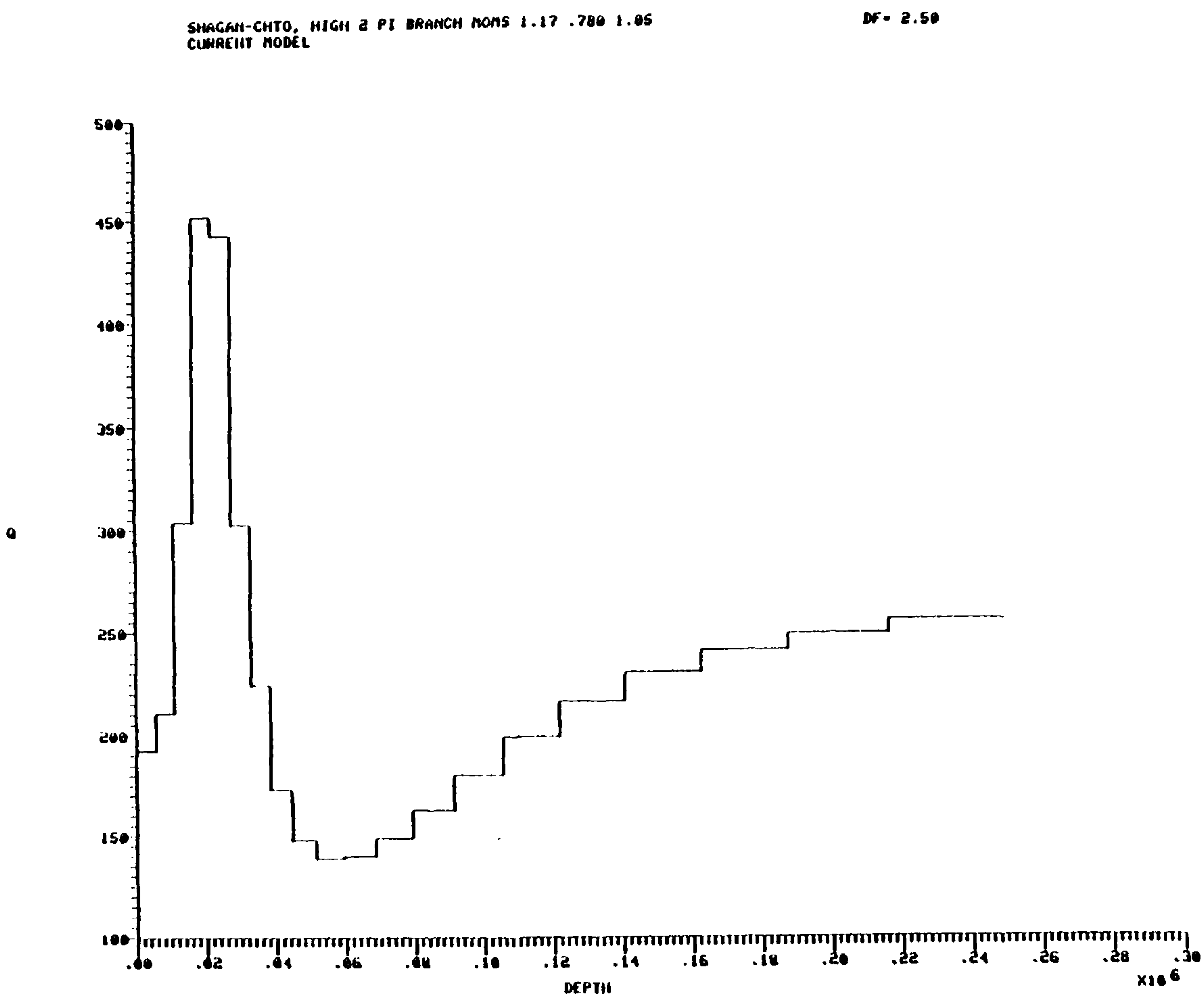

SHAGAN-CHTO, HIGH 2 PI BRANCH NOMS 1.17 .780 1.05
CURRENT MODEL
DF= 2.50
Q
500
450
400
350
300
250
200
150
100
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30
X10 6
DEPTH

Figure 20.4

SHAGAN-CHTO STRUCTURE

I	DEPTH	THICK	ALPHA	BETA	RHO	QQM
1	5.521+003	5.521+003	5.608+003	3.148+003	2.446+003	1.923+002
2	1.104+004	5.521+003	5.690+003	3.194+003	2.476+003	2.107+002
3	1.656+004	5.521+003	5.961+003	3.346+003	2.575+003	3.038+002
4	2.209+004	5.521+003	6.134+003	3.471+003	2.656+003	4.514+002
5	2.761+004	5.521+003	6.250+003	3.508+003	2.660+003	4.423+002
6	3.313+004	5.521+003	6.227+003	3.495+003	2.672+003	3.024+002
7	3.865+004	5.521+003	6.683+003	3.751+003	2.838+003	2.241+002
8	4.462+004	5.965+003	6.750+003	3.789+003	2.863+003	1.728+002
9	5.150+004	6.885+003	6.907+003	3.377+003	2.920+003	1.476+002
10	5.945+004	7.948+003	7.140+003	4.008+003	3.005+003	1.384+002
11	6.863+004	9.175+003	7.397+003	4.152+003	3.099+003	1.397+002
12	7.922+004	1.059+004	7.629+003	4.282+003	3.183+003	1.484+002
13	9.144+004	1.222+004	7.307+003	4.382+003	3.248+003	1.524+002
14	1.056+005	1.411+004	7.931+003	4.452+003	3.294+003	1.798+002
15	1.218+005	1.629+004	8.003+003	4.492+003	3.328+003	1.985+002
16	1.407+005	1.880+004	8.015+003	4.499+003	3.324+003	2.159+002
17	1.624+005	2.170+004	7.980+003	4.479+003	3.311+003	2.300+002
18	1.874+005	2.505+004	7.937+003	4.455+003	3.236+003	2.404+002
19	2.163+005	2.892+004	7.935+003	4.454+003	3.295+003	2.484+002
20	2.497+005	3.339+004	7.992+003	4.486+003	3.316+003	2.551+002

Figure 20.5.

Figures 21.1 through 21.5 are on the following pages.

Figure 21. Path 7: SHAGAN-KAAO

Distance: 1884 km
Azimuth: 22.1°
Instrument: ASRO-LP
Events Processed: 318

Description: This is a very difficult station to process because of a cleanly bifurcated group velocity curve above 0.04 Hertz. The split is quite obvious in the narrow band filter, but the phase matched filter simply cannot handle it, wanting to jump back and forth between the branches. To process this seismogram, we selected the upper group velocity curve and performed no iterations with the phase matched filter. The final result (synthetic seismogram made using the structure) is a fairly good match to the original, but we cannot express much confidence in the results. The same problem will arise in any further data processing at this station; so it should probably be avoided if possible.

```
SEC 8, OPTION(H-HELP) ? >L
SEC 8, OPTION(H-HELP) ? >1 L
 GROUP VELS PICKED:
IDX  FREQ  GRPV  AMPL

  1  .0000   .000   .000
  2  .0130  3.787   .113
  3  .0163  3.700   .120
  4  .0201  3.469   .163
  5  .0230  3.245   .234
  6  .0260  3.166   .279
  7  .0298  3.038   .352
  8  .0336  2.943   .521
  9  .0366  2.905   .755
 10  .0390  2.894   .935
 11  .0413  2.888  1.000
 12  .0435  2.881   .957
 13  .0453  2.871   .822
 14  .0468  2.843   .630
 15  .0494  2.803   .460
 16  .0524  2.786   .349
 17  .0557  2.783   .277
 18  .0587  2.785   .226
 19  .0605  2.786   .179
 20  .0625  2.768   .135
 21  .0670  2.749   .108
 22  .0729  2.740   .096
 23  .0786  2.736   .096
 24  .0831  2.734   .103
 25  .0862  2.732   .109
 26  .0880  2.730   .111
 27  .0891  2.727   .107
 28  .0900  2.719   .098
 29  .0913  2.703   .086
 30  .0932  2.686   .074
SEC 8, OPTION(H-HELP) ? >
```

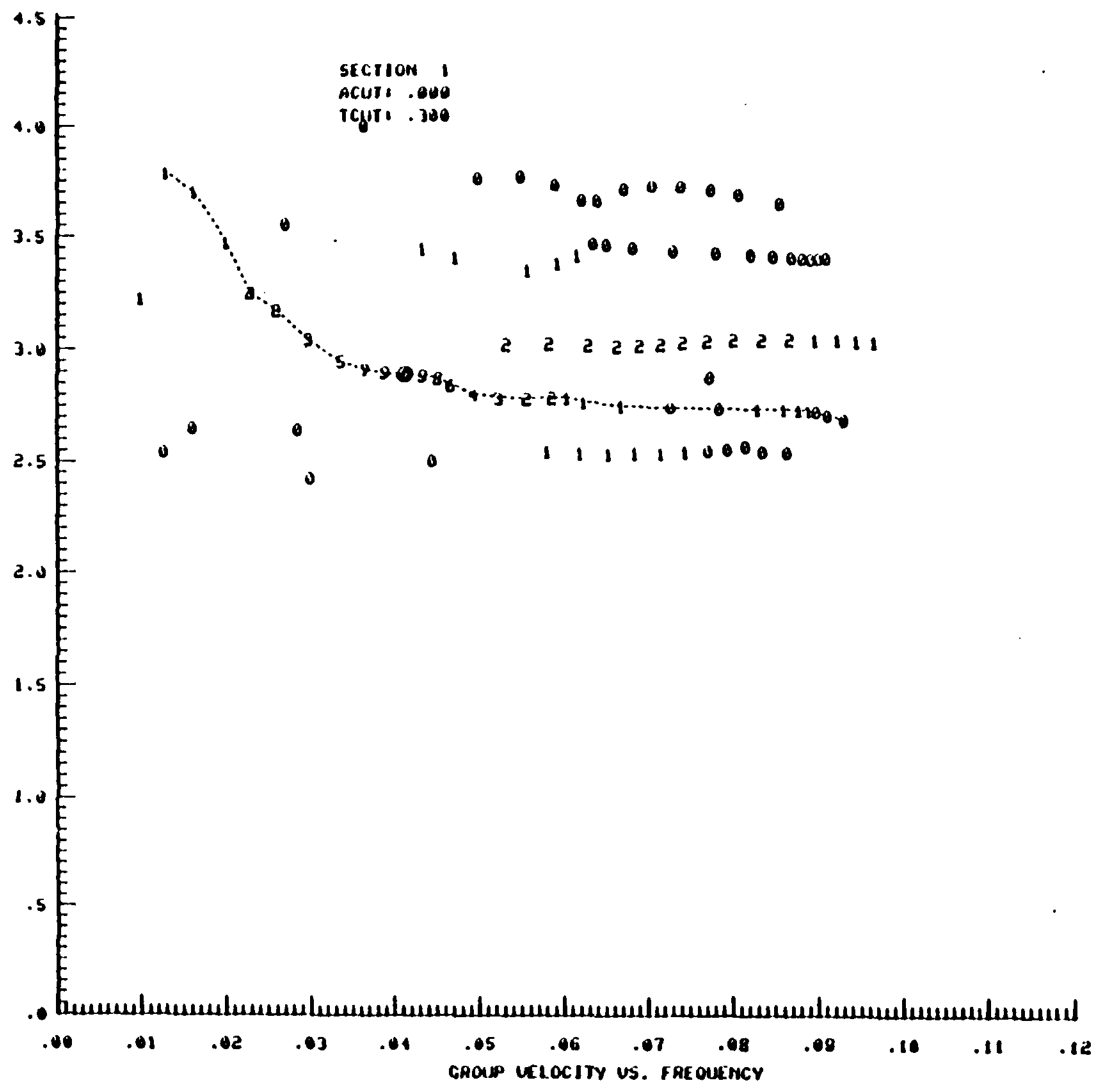


Figure 21.1.

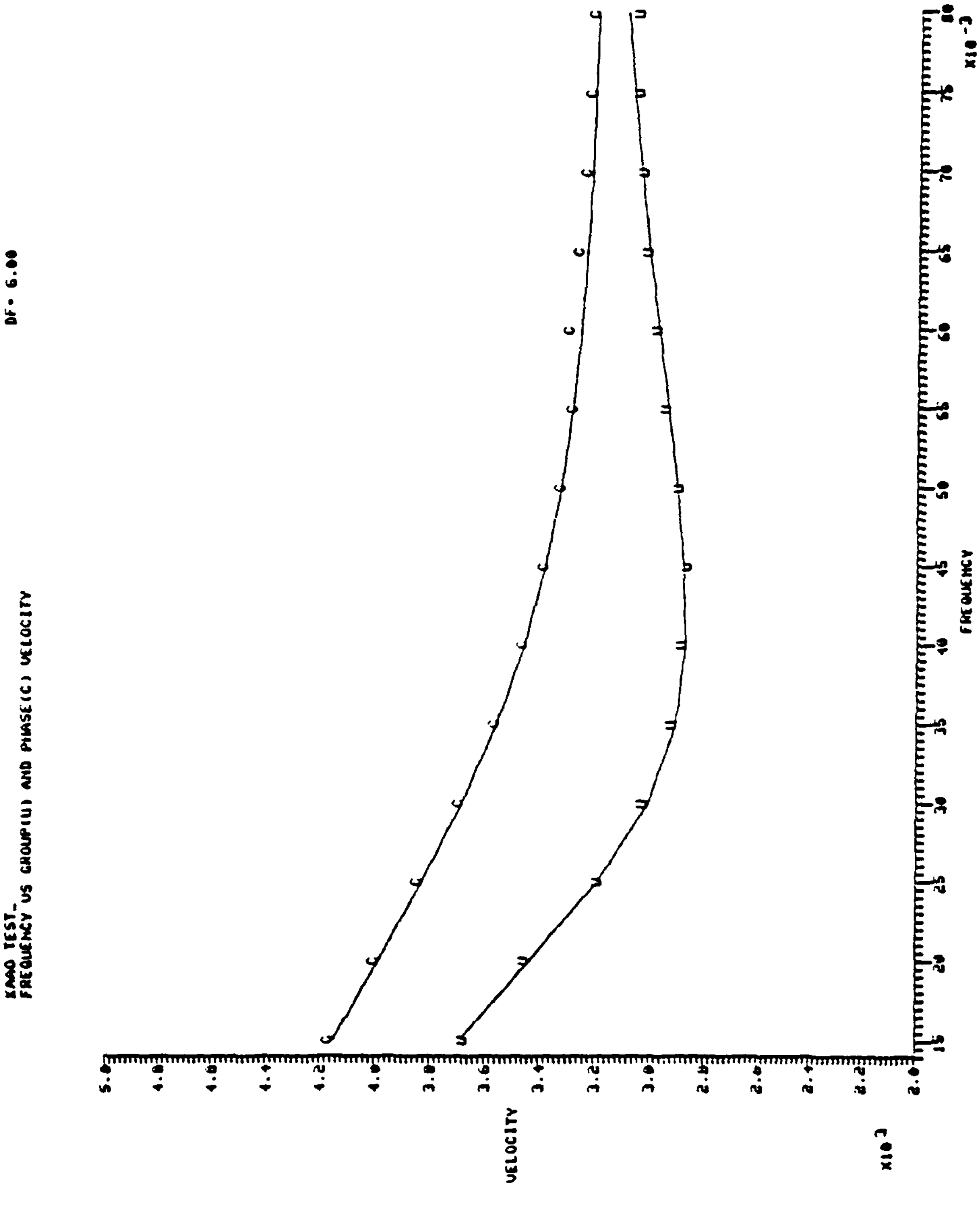

KAAO TEST
FREQUENCY VS GROUP(U) AND PHASE(C) VELOCITY
DF- 6.00
VELOCITY
X10^-3
FREQUENCY
X10^-3

Figure 21.2.

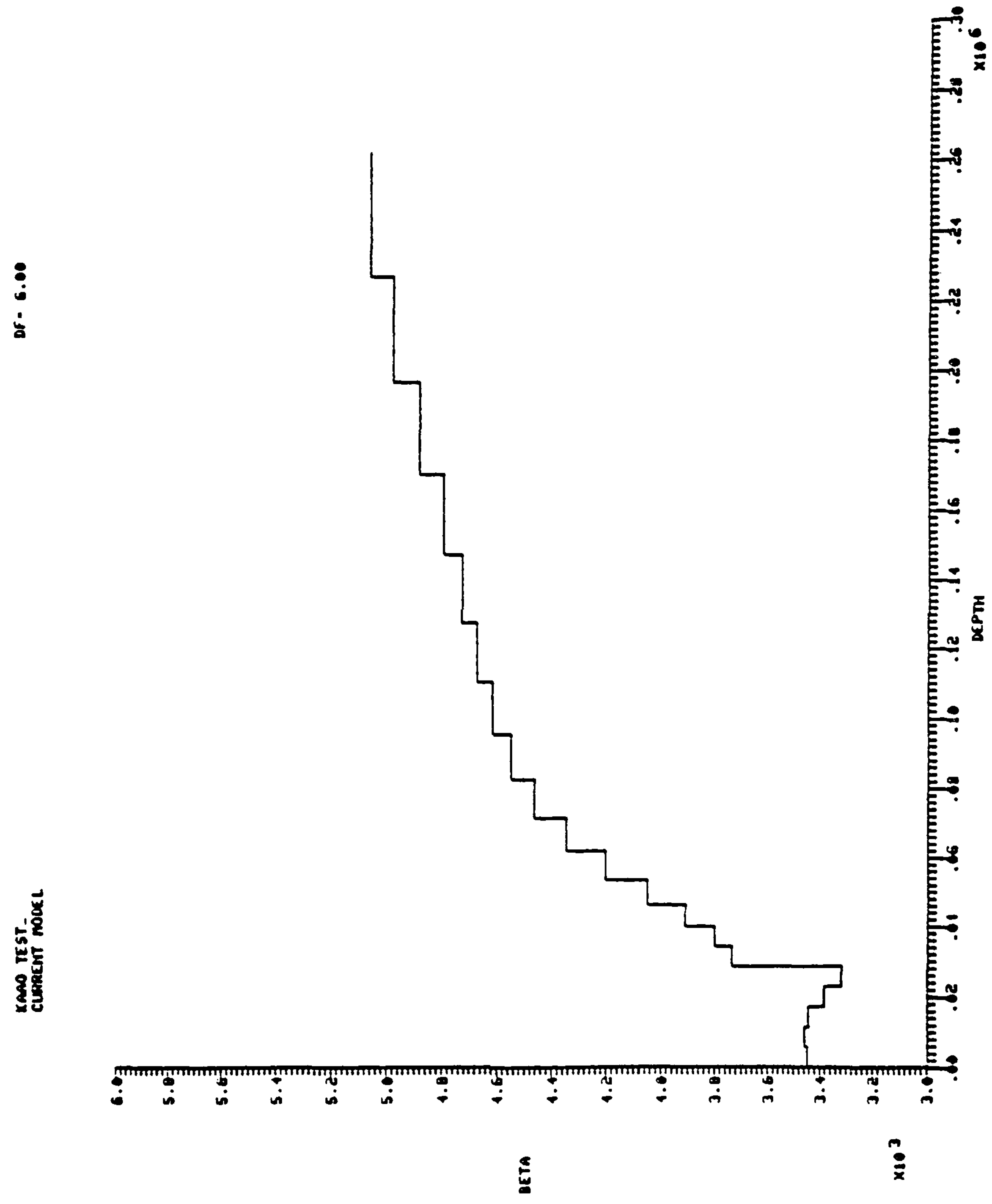


Figure 21.3.

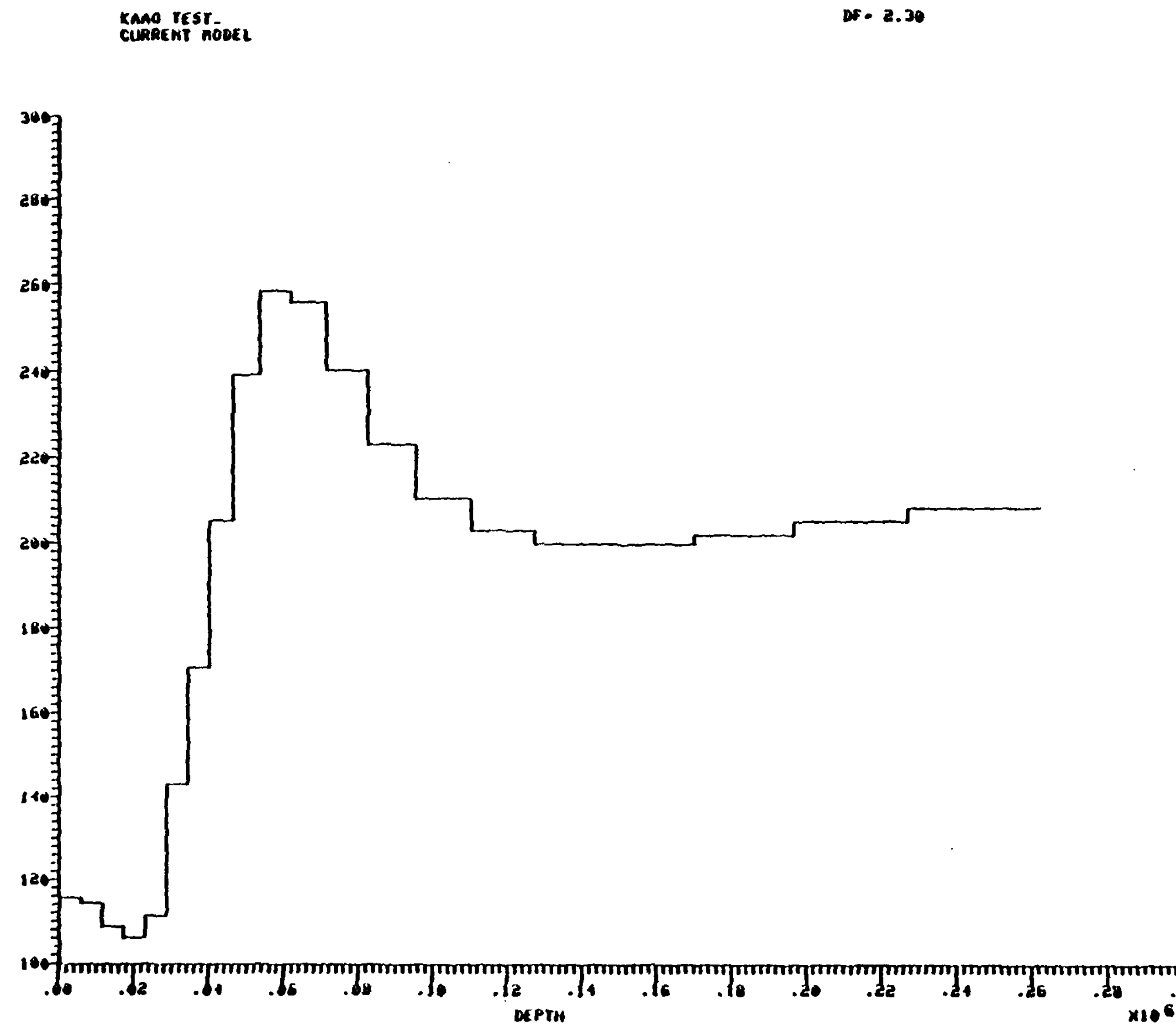

KAAO TEST.
CURRENT MODEL
DF- 2.30
Q
300
280
260
240
220
200
180
160
140
120
100
.00
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30
DEPTH
X10^6

Figure 21.4

SHAGAN-KAAO STRUCTURE

I	DEPTH	THICK	ALPHA	BETA	RHO	QGM
1	5.737+003	5.737+003	6.141+003	3.447+003	2.641+003	1.155+002
2	1.147+004	5.737+003	6.159+003	3.457+003	2.647+003	1.142+002
3	1.721+004	5.737+003	6.134+003	3.443+003	2.638+003	1.087+002
4	2.255+004	5.737+003	6.025+003	3.382+003	2.598+003	1.053+002
5	2.869+004	5.737+003	5.909+003	3.317+003	2.556+003	1.112+002
6	3.442+004	5.737+003	6.656+003	3.736+003	2.329+003	1.431+002
7	4.016+004	5.737+003	6.772+003	3.601+003	2.371+003	1.708+002
8	4.640+004	6.242+003	6.966+003	3.911+003	2.342+003	2.053+002
9	5.362+004	7.212+003	7.217+003	4.051+003	3.033+003	2.392+002
10	6.195+004	8.333+003	7.490+003	4.204+003	3.133+003	2.584+002
11	7.158+004	9.628+003	7.744+003	4.347+003	3.226+003	2.558+002
12	8.270+004	1.112+004	7.951+003	4.463+003	3.301+003	2.402+002
13	9.556+004	1.285+004	8.102+003	4.548+003	3.356+003	2.230+002
14	1.104+005	1.485+004	8.220+003	4.614+003	3.399+003	2.183+002
15	1.276+005	1.716+004	8.318+003	4.669+003	3.435+003	2.028+002
16	1.474+005	1.982+004	8.418+003	4.725+003	3.471+003	1.996+002
17	1.703+005	2.290+004	3.537+003	4.792+003	3.515+003	1.995+002
18	1.966+005	2.646+004	8.692+003	4.879+003	3.571+003	2.016+002
19	2.274+005	3.058+004	3.861+003	4.974+003	3.633+003	2.048+002
20	2.627+005	3.533+004	3.009+003	5.257+003	3.687+003	2.079+002

Figure 21.5.

III. CONCLUSIONS AND RECOMMENDATIONS

We have developed a comprehensive surface wave analysis package and have used it to obtain path corrections for paths from the Shagan River explosion test sites to several SRO stations. This analysis provides:

1. An average velocity and Q structure for each path.
2. A scalar moment estimate for each event processed.
3. A Green's function for each path.

The Green's function may be used to perform a moment tensor inversion or to construct a matched filter for events from a given area. In addition, the processing provides a description of station quality, by identifying paths with strong multipathing, scattering, or variable group velocities.

The procedure used to obtain a path correction is to use narrow band filtering and phase matched filtering to obtain phase and group velocities from surface wave seismograms, invert these to find the average earth structure along the path, use the structure to generate a synthetic surface wave spectrum and invert the synthetic/observed spectral ratio for moment and Q structure. For the paths processed to date, we find very consistent phase and group velocities at most stations, which in turn produce well constrained shear velocity structures. The attenuation measurements obtained using a single station are not as accurate as velocity measurements; however, we are able to obtain reasonable Q structures and consistent moments in most circumstances. The method used to obtain Q structures is a new and promising technique. However, a comprehensive error and trade-off analysis has not yet been performed. This should be done as part of a continuing effort to make further path corrections.

The interactive format of the surface wave analysis programs allows data to be processed very quickly. Once seismograms and all relevant information have been obtained for a given path, a path correction can be obtained in about two hours.

The procedure we have developed works well and is the best method available for obtaining path corrections from a known test site to a set of receiving stations. There are two aspects of the problem, however, which have not yet been addressed and which may be important to the yield estimation and discrimination problems. First, the method can only be applied to known test areas so that seismograms for several large explosions are available for processing. While the method could be applied to a single isolated explosion, it is preferable to have more than one event available in order to check the stability of the results based on internal consistency. Furthermore, a moment tensor inversion cannot be performed until all relevant path corrections for a given source area have been determined. Second, the method assumes that the earth can be adequately modeled by plane-layers with constant velocities and constant Q. While this approximation is usually adequate, the effects of lateral heterogeneities and scattering are often very clear in the initial stage of data processing.

In order to apply the path correction procedure to new regions of the earth, the algorithms could be modified to allow the use of earthquakes as well as explosions. A small amount of code development would be required to extend the method to use earthquakes. No changes are required for structure inversion, but Q inversion requires the construction of a synthetic spectrum using an earthquake (double-couple) source instead of an explosion source. Of course, application of the method to an earthquake requires knowledge of the earthquake focal mechanism and depth. This information can be obtained with sufficient accuracy from body wave observations. The advantage of applying the method to earthquakes is that earthquakes occur almost everywhere. If an isolated explosion occurs, then earthquakes in the area can be used to constrain the velocity and Q structures.

A crucial question in the application of surface waves to yield estimation is how the surface waves are affected by lateral structure variation and scattering. The use of phase matched filtering removes well separated multipath arrivals and scattered waves in order to obtain more accurate group velocities. It is not clear what effect these multiple arrivals have on the observed amplitudes, however. If there is a large amount of scattered energy, should it be included in the primary arrival under the assumption that it was scattered from the primary arrival, or excluded since we do not know the origin of the scattered waves, or should we avoid paths which show a large amount of scattering?

To summarize, we have developed a comprehensive surface wave analysis package which allows path corrections to be quickly determined. We recommend the following items as topics for continuing research.

1. A comparison of our observations of multiple arrivals and scattering with theoretical studies of these effects in order to estimate their influence on moment and attenuation estimates.

2. A comprehensive error and tradeoff analysis of the Q inversion algorithm.

3. Extension of the method to allow the use of earthquakes to obtain path corrections in isolated areas.

IV. REFERENCES

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APPENDIX 1

FILE FORMATS FOR SURFACE WAVE ANALYSIS PACKAGE

Earth Structure File

Use: Written or read by INVERT
Read by SYNSRF (Part 1 and Part 2)

Format: Read by following statements

```
      READ(IEMF, 1) HED
    1 FORMAT(A80)
      READ(IEMF,*) NLAYER, NUNITS
      DO 10 I = 1, NLAYER
   10 READ(IEMF,*) THK(I), AL(I), BE(I), RHO(I), QM(I), QB(I)
```

Definitions:

IEMF = File number
HED = 80 Character header
NLAYER = Number of layers
NUNITS = 0 for MKS units
= 1 for Seismological units (km, km/sec, gm/cm^3)

THK(I) = Thickness of layer I
AL(I) = Compressional velocity
BE(I) = Shear velocity
RHO(I) = Density
QM(I) = Shear quality factor
QB(I) = Bulk quality factor

Notes: Free format read is used to make input easier. This means variables do not have to be lined up in columns, but means that six numbers must be input on every line. If either the bulk Q or shear Q is set equal to zero, the program will set them to a large number. Both INVERT and SYNSRF use MKS units internally, but seismological units may be used as input for conveneience.

Observed Dispersion File

Use: Written by TELVEL

Also written by AVEDAT, INTERQ

Read by INVERT, AVEDAT, INTERQ

Format: Read by the following statements

```
      READ(ITEL,1) HED
    1 FORMAT(A80)
      READ(ITEL,2) NF, DIST, DLYT, PHACOR
    2 FORMAT(I5,3E15.5)
      DO 10 I = 1, NF
   10 READ(ITEL,3) ARL(I), MODE(I), F(I), U(I), C(I), DU(I), DC(I),
     +AMP(I), DAMP(I)
    3 FORMAT (A1,I4,7E10.4)
```

Definitions:

HED -- 80 Character header

NF -- Number of frequencies

DIST -- Distance from source to receiver (km)

DLYT -- Delay time (start of original seismogram)

PHACOR -- Initial source phase

ARL -- Single character variable, R for Rayleigh, L for Love

MODE -- Mode number of observed data point (usually 1)

F -- Frequency of observed data point

U -- Group velocity

C -- Phase velocity

DU -- Standard deviation in U

DC -- Standard deviation in C

AMP -- Observed, instrument corrected spectral amplitude

DAMP -- Standard deviation in AMP

Notes:

The true observed phase is given by

$$\phi = -\frac{2\pi F * DIST}{C} + PHACOR$$

Units are in kilometers for distance, km/sec for velocities, transformed input units for amplitude.
DU, DC, DAMP are set to zero by TELVEL, and are calculated by post processing utility codes (AVEDAT, INTERQ)
For array data, several files may be combined into a single file, and AMP, DAMP replaced with attenuation coefficients γ for multistation Q inversion (INTERQ).

Dispersion File

Use: Written by SYNSRF (Part 1)

Also written by INVERT

Read by SYNSRF (Part 2)

Format: Unformatted file read by following statements

```
      READ(IDISP) HED
      READ(IDISP) NRL, NMODE
      DO 10 I = 1, NMODE
      READ(IDISP) NF, (F(J,I), J = 1,NF), (C(J,I), J = 1,NF)
   10 MF(I) = NF
```

Definitions:

HED -- 80 Character header

NRL -- 1 for Rayleigh

2 for Love

NMODE -- Number of modes

MF(I) -- Number of frequencies for mode I

F(J,I) -- Frequency J for mode I

C(J,I) -- Phase velocity J for mode I

Notes: F and C are double precision variables on this file

All units are MKS

Eigenfunction File

Use: Written by SYNSRF (Part 2)
Read by SYNSRF (Part 3) for source or path
Read by EXCITE

Format: Unformatted file read by following statements

```
      READ(IEIG) HED
      READ(IEIG) NRL, NMODE, DEPTH, LAYER, ALPHA, BETA, RHO
      DO 10 I = 1, NMODE
      READ(IEIG) NF, (F(J,I), J = 1, NF), (CU(J,I), J = 1, NF),
        (U(J,I), J = 1, NF), (AR(J)I), J = 1, NF),
        (EL(J,I), J = 1, NF), (GA(J,I), J = 1, NF),
        ((EIGEN(J,K,I), J = 1, NF), K = 1, NQ)
   10 MF(I) = NF
```

Definitions:

HED -- 80 Character header
NRL -- 1 for Rayleigh
2 for Love
NMODE -- Number of modes
DEPTH -- Source depth
LAYER -- Source layer number
ALPHA -- Source layer compressional velocity
BETA -- Source layer shear velocity
RHO -- Source layer density
MF(I) -- Number of frequencies for mode I
F(J,I) -- Frequency J for mode I
C(J,I) -- Phase velocity
U(J,I) -- Group velocity
AR(J,I) -- Harkrider's A_R (Rayleigh) or A_L (Love)
EL(J,I) -- Ellipticity
GA(J,I) -- Gamma, attenuation coefficients
NQ -- Number of eigenfunctions = 4 for Rayleigh, 2 for Love
EIGEN(J,K,I) -- Eigenfunction K for mode I and frequency J evaluated at source depth

Notes: All quantities are single precision

All quantities are in MKS units

Notation follows Harkrider (1964, 1970)

Seismogram File

Use: Written by SYNSRF (Part 3)

Read by RLSEIS (To convert to REALIO format)

Format: Unformatted file read by following statements

```
READ(ISYN) HED1, HED2, HED3
READ(ISYN) NF, DF, (SPEC(I), I = 1, NF)
READ(ISYN) NT, DT, TMIN, (SEIS(I), I = 1, NT)
```

Definitions:

HED1, HED2, HED3 are 3-80 Character headers

NF -- Number of frequencies

DF -- Frequency spacing

SPEC(I) -- Complex spectrum at frequency (I -1)*DF

NT -- Number of time points in synthetic seismogram

DT -- Time spacing

TMIN - Start time

SEIS(I) -- Seismogram, time series at time TMIN + (I -1)*DT

Notes: All quantities are in MKS units

Spectrum is stored as real and imaginary parts

Transform of spectrum will start at T = 0, not T = TMIN

Fourier transform is defined by:

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}\,dt$$

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}\,d\omega$$

Decomposed Spectral File

Use: Written by SYNSRF (Part 3)

Format: Unformatted file read by following statements

```
      READ(ISPEC) HED1, HED2, HED3
      READ(ISPEC) NMODE, NF, R, AMO, ALPHA, BETA, RHO
      READ(ISPEC) (F(I), I = 1, NF)
      READ(ISPEC) (AINST(J), PINST(I), I = 1, NF)
      READ(ISPEC) (ASRC(I), PSRC(I), I = 1, NF)
      DO 10 J = 1, NMODE
   10 READ(ISPEC)(AMP(J,I),PHASE(J,I), GAMMA(J,I), I = 1, NF)
```

Definitions:

HED1, HED2, HED3 -- 3-80 Character headers
NMODE -- Number of modes
NF -- Number of frequencies
R -- Distance (meters)
AMO -- Source moment
ALPHA, BETA, RHO -- Elastic constants of source region
F(I) -- Array of frequencies
AINST(I), PINST(I) -- Instrument amplitude and phase at frequency F(I)
ASRC(I), PSRC(I) -- Source (RVP) amplitude and phase
AMP(I,J), PHASE(I,J), GAMMA(I,J) -- Surface wave amplitude, phase, and attenuation coefficients for mode J, and frequency I

Notes: All quantities single precision, real, MKS units; frequencies are those used for synthetic, so there may be many.This file is intended for further analysis of individual parts of the spectrum. The spectrum of the complete complex seismogram S(I) is given by:

$$S(I) = AINST(I) * ASRC(I) * CEXP(0., PINST(I) + PSRC(I))* \sum_J AMP(I,J) * CEXP(- R * GAMMA(I,J), PHASE(I,J))$$

Excitation Function (Path Correction) File

Use: Written by EXCITE

Format: Read by following statements

```
      READ(IEX, 1) HED
      READ(IEX, 2) ARL, NF, R, AE
      DO 10 I = 1, NF
   10 READ (IEX, 3) F(I), C(I), AR(I), GAM(I), EPS(I), GREEN(I)
   20 READ(IEX, 4) NF1, DEPTH
      DO 30 I = 1, NF1
   30 READ(IEX, 5) F1(I), AR1(I), RN(I), RP(I), RQ(I), RS(I)
```

Return to 20 for more depths until NF1 = 0

```
    1 FORMAT(A80)
    2 FORMAT(A5, I5, 2E10.4)
    3 FORMAT(7E10.4)
    4 FORMAT(I5, E10.4)
    5 FORMAT(7E10.4)
```

Definitions:

HED -- 80 Character header
ARL -- R for Rayleigh
NF -- Number of frequencies
R -- Distance in meters
AE -- Earth's radius in meters
F(I) -- Frequency
C(I) -- Phase velocity at frequency F(I)
AR(I) -- Harkrider's A_R
GAM(I) -- Gamma, attenuation coefficients
EPS(I) -- Ellipticity
GREEN(I) -- Complex Green's function
DEPTH -- Source depth
NF1 -- Number of frequencies for this depth
F1(I) -- Frequencies for this depth
C1(I) -- Phase velocity
AR1(I) -- Harkrider's A_R at frequencies F1
RN(I), RP(I), RQ(I), RS(I) -- Excitation functions as defined by Kanamori and Given

Notes: This file is the interface between the Surface Wave Analysis Package and Sierra Geophysics Moment Tensor Inversion Program.

This file is constructed from any number of Eigenfunction files generated by SYNSRF, so it may or may not have the same set of frequencies for each depth.

The Green's function GREEN(I) is defined by:

$$\mathrm{GREEN} = \frac{e^{i\frac{\pi}{4}}\, e^{\frac{-i\omega r}{c}}\, e^{-\gamma r}}{\sin(r/a_e)}$$

The radius of the earth a_e is written on the file because it is used in constructing the excitation functions. Kanamori and Given's excitation functions are called N_R, P_R, Q_R, S_R.

Explosion RVP File

Use: Generated by S-CUBED explosion codes
Read by SYNSRF

Format: Read by following statements

```
      READ(IRVP,1) HED
      READ(IRVP,1) HED2
      READ(IRVP,2) YIELD
      READ(IRVP,1) JUNK
      READ(IRVP,3) REL, VP, VS
   10 READ(IRVP,4) F(I), AMRVP(I), PHRVP(I), LAST
      AMRVP(I) = AMRVP(I) * 1.E-6
      IF(LAST. NE.1) Go to 10
    1 FORMAT(A80)
    2 FORMAT(10X, E10.4)
    3 FORMAT(3F10.2)
    4 FORMAT(E15.7, 30X, 2E15.7, I5)
```

Definition:

HED1, HED2 -- 80 Character headers
YIELD -- Original explosion yield for calculation
JUNK -- Nothing, blank line
REL -- Elastic radius
VP, VS -- Elastic constants of source
F(I) -- Frequency
AMRVP(I) -- Amplitude of RVP, scaled to meters cubed
PHRVP(I) -- Phase of RVP

Notes:

Check with Norton Rimer for accuracy of YIELD, VP, VS.
To scale from yield YOLD to YNEW

AMRVP ~ YNEW/YOLD
F ~ (YOLD/YNEW) ** (1/3)
REL ~ (YNEW/YOLD) ** (1/3)

Instrument Files

Use: Read by SYNSRF

Types: There are three types — polynomial coefficients (preferred), and two formats for tabular responses, corresponding historically to S-CUBED long period and short period instrument responses.

Format of Polynomial File:

The following format is used for polynomial files:

```
READ(INST,1) HED
READ(INST,*) INUM
IR = INUM + 1
READ(INST,*) (POLYN(I), I = 1, IR)
READ(INST,*) IDEN
IR = IDEN + 1
READ(INST,*) (POLYD(I), I = 1, IR)
```

Definitions: A polynomial response is written in the form

$$P(s) = \frac{\sum_{i=0}^{N} A_i s^i}{\sum_{i=0}^{M} B_i s^i}$$

where $s = i\omega$

N = INUM the degree of the numerator polynomial, with coefficients A_i = POLYN(I) starting from degree zero

M = IDEN the degree of the denominator, with coefficients B_i = POLYD(I), starting from degree zero

Note: A program (ZERPOL) is available to transform poles and zeros into polynomial coefficients. Another (RLINST) puts a polynomial file into REALIO format for use with TELVEL and other REALIO routines.

Format of S3LP file:

```
      READ(INST,1) NF
      DO 10 I =1, NF
      READ(INST,2) PERIOD, AMP(I), PHM2PI
      FR(I) = 1./PERIOD
   10 PHS(I) = - 2. * PI * PHM2PI
    1 FORMAT(I3)
    2 FORMAT(F8.0, 2F12.0)
```

Definitions:

NF = Number of frequencies
AMP = Instrument amplitude
PHS = Instrument phase
FR = Frequencies

Note: Phase stored as minus phase/2π

Format of S3SP file:

```
      READ(INST,1) HED
      READ(INST,2) NF
      DO 10 I = 1, NF
   10 READ(INST,3) AMP(I), PHS(I), FR(I)
    1 FORMAT(A80)
    2 FORMAT(I10)
    3 FORMAT(3E15.5)
```

Notes: The S3LP and S3SP notations are historical only. An instrument response may be used with either format, regardless of whether it is a long period or short period instrument.

Warning: Some instrument files have a factor of minus one built in, apparently to change vertical down to vertical up in old surface wave codes. Check before using.

REALIO Files

REALIO files are designed for internal use by subroutines in the time series analysis package (Berger, et al., 1979) which are used by TELVEL. The exact format of the REALIO files is machine dependent, so it is not given here, however files may be read or written by a call to subroutine REALIO. The following commands cause a file to be opened and the array SEIS containing NPTS points read in. The underscore is used as a delimiter here.

```
CHARACTER*80 FILENM
DIMENSION SEIS (NPTS)
CALL GETSTR ('ENTER SEISMOGRAM FILENAME _', FILENM)
CALL GETLU (FILENM, LU,-1)
CALL REALIO(SEIS,1,NPTS,LU,0)
```

The call to GETSTR reads the file name from the keyboard.

The call to GETLU returns a logical unit number and opens the file. The -1 used as the third parameter indicates an existing file. A number greater than zero opens a new file.

The call to REALIO reads the file into the array SEIS. The use of zero as the fifth parameter causes the file to be read. Similarly if this parameter is greater than zero, the array is written to the file.

For more information on the use of these routines, see the report by Berger et al., (1979). The program RLSEIS2 is easily modified to put any file into REALIO format.

APPENDIX 2

UTILITY PROGRAMS

Several short programs are available for use with the surface wave analysis package. The most important are listed here.

EXCITE -- Converts eigenfunction files to an excitation function file. Requires only file names as input.

RLSEIS -- Converts seismogram file from SYNSRF to REALIO format.

RLSEIS2 -- Reads in a seismogram, plots, truncates, demeans, detrends, and tapers, and writes file in REALIO format. Easily modified to read any format. Requires file names and number of points as input.

RLINST -- Converts polynomial instrument file to REALIO format.

AVEDAT -- Reads TELVEL files, finds average phase and group velocities and standard deviations, and relative moments. Outputs a new TELVEL file for path.

INTERQ -- Reads TELVEL files for an array of stations, finds attenuation coefficients and average phase and group velocities and standard deviations. Outputs a new TELVEL file with amplitudes replaced by attenuation coefficients.

ZERPOL -- Turns list of poles and zeroes for instrument response into polynomial coefficients.

APPENDIX 3

SURFACE WAVE NOTATION

The surface wave code SYNSRF uses the notation of Harkrider (1964, 1970) for surface waves with some minor modifications displacement is given by:

$$u = \frac{\chi(\theta,h)A_R}{\sqrt{2\pi\omega c a_e \sin(r/a_e)}} S(\omega)e^{i(1+2m)\frac{\pi}{4}} e^{-ikr_e - \gamma r} \epsilon$$

where χ are functions defined by Harkrider (1970), $S(\omega)$ is a source function and $m = 1$ for double couple and 0 for point force or explosion.

$\epsilon = -1$ for vertical component Rayleigh wave (positive up)

$\epsilon = ie$, where e = ellipticity for radial component

$\epsilon = i$ for Love wave

For an explosion:

$S = -8\pi\mu\,\Psi_\infty$

$\chi = (E_1 - E_3/2\mu)$

For an impulsive point force:

$S = iI_0c$ (I_0 = Impulse)

$\chi = -E_2$ (downward)

$\chi = iE_1 \cos\theta$ (radial)

For a double couple:

$S = iM_0$ (M_0 = Moment)

$\chi = [(2\beta^2/\alpha^2 - 3/2)E_1 - E_3/\rho\alpha^2] + \frac{E_1}{2}\cos 2\theta$ 45° dip slip

$\chi = -E_1 \sin 2\theta$ strike slip

Here θ is clockwise from north = - azimuth which is used in interactive input. Note that near the free surface at long periods $E_1 < 0$, $E_2 > 0$, and $e < 0$, while E_3/μ is small. Thus the initial phase ϕ_0 may be found from these expressions. For an explosion

$$\phi_0 = -\frac{3}{4}\pi$$

For a downward point force

$$\phi_0 = +\frac{3}{4}\pi.$$

For a point force where velocity is computed, multiply by $i\omega$ so

$$\phi_0 = -\frac{3}{4}\pi.$$

We have used the following shorthand notation for Harkrider's eigenfunctions:

$$E_1 = \dot{u}^*(h)/\dot{w}_0$$

$$E_2 = \dot{w}(h)/\dot{w}_0$$

$$E_3 = \sigma^*(h)/(\dot{w}_0/c)$$

$$E_4 = \tau(h)/(\dot{w}_0/c)$$

APPENDIX 4

CONVERSION OF HARKRIDER EIGENFUNCTIONS TO KANAMORI AND GIVEN EXCITATION FUNCTIONS

We want to convert the eigenfunctions defined by Harkrider (1964, 1970) into the excitation functions defined by Kanamori and Given (1981). The easiest way to do this is by comparing their final expressions for farfield Rayleigh waves. In the notation of Harkrider, the vertical component of the Rayleigh wave (positive up) is given by:

$$u = \frac{A_R}{\sqrt{2\pi\omega c a_e \sin\Delta}} \chi(\theta,h)\, e^{-\gamma r}\, e^{\frac{-i\omega r}{c}} \tag{1}$$

The function χ depends on source type and source depth. For an explosion with a step function time history:

$$\chi = 8\pi\mu\Psi_\infty\, e^{\frac{-3\pi i}{4}}\left(\frac{E_3}{2\mu} - E_1\right) \tag{2}$$

And for a double couple with a step function time history:

$$\chi = M_o\, e^{i\frac{\pi}{4}}\left(d_o + i[d_1 \sin\theta + d_2 \cos\theta] + d_3 \sin 2\theta + d_4 \cos 2\theta\right) \tag{3}$$

where the functions d_i are defined by Harkrider (1970, page 1938). Here θ is measured west from north.

In the notation of Kanamori and Given, using a moment tensor representation for the source, again assuming a step function time history, the farfield vertical displacement is given by:

$$u = \frac{1}{\sqrt{\sin\Delta}}\, e^{i\frac{\pi}{4}}\, e^{\frac{-i\omega r}{c}}\, e^{-\gamma r}\, F(\theta,h) \tag{4}$$

where

$$F(\theta,h) = -P_R[M_{xy}\sin 2\theta - \frac{1}{2}(M_{yy} - M_{xx})\cos 2\theta] \tag{5}$$

$$+ \frac{1}{3}[S_R + N_R] M_{zz}$$

$$+ \frac{1}{6}[2N_R - S_R](M_{xx} + M_{yy})$$

$$+ i\, Q_R(M_{yz}\sin\theta + M_{xz}\cos\theta)$$

The equivalence between the excitation function P_R, Q_R, S_R, N and the Harkrider eigenfunctions may be found by comparing equations (1) and (4) for special cases. For an explosion, $M_{xx} = M_{yy} = M_{zz} \equiv M_o$, so equation (5) reduces to

$$F(\theta,h) = M_o N_R \tag{6}$$

The moment of an explosion is defined by

$$M_o = 4\pi\rho\alpha^2\Psi_\infty = 4\pi(\lambda + 2\mu)\Psi_\infty \tag{7}$$

so comparing equations (1) and (4)

$$\boxed{N_R = \frac{+A_R}{\sqrt{2\pi\omega c a_e}} \left(\frac{2\mu}{\lambda + 2\mu}\right)\left(E_1 - \frac{E_3}{2\mu}\right)} \tag{8}$$

Second, consider a strike slip double couple. The only nonvanishing coefficient in Equation 3 is $d_3 = -E_1$. Using $M_{xy} = -M_o$, Equation (5) reduces to $F = + M_o P_R \sin 2\theta$. Comparing equations again, we get

$$\boxed{P_R = \frac{-A_R}{\sqrt{2\pi\omega c a_e}} E_1} \tag{9}$$

Next, consider a horizontal dip slip double couple ($M_{xz} = + M_o$). We have $d_2 = E_4/\mu$ and $F = + iM_oQ_R \cos\theta$. So

$$\boxed{Q_R = \frac{+A_R}{\sqrt{2\pi\omega c a_e}} \quad \frac{E_4}{\mu}} \tag{10}$$

Finally, a 45° dip slip double couple has $M_{zz} = M_o$, $M_{yy} = - M_o$ and

$$d_4 = \frac{1}{2} E_1, \; d_o = - \frac{1}{2}\left[\frac{3\lambda + 2\mu}{\lambda + 2\mu} E_1 + \frac{2}{\lambda + 2\mu} E_3\right] \quad .$$

We also have

$$F = \left[- P_R \frac{1}{2} \cos 2\theta + \frac{1}{2} S_R\right] M_o \quad .$$

So

$$\boxed{S_R = \frac{-A_R}{\sqrt{2\pi\omega c a_e}} \left[\frac{3\lambda + 2\mu}{\lambda + 2\mu} E_1 + \frac{2}{\lambda + 2\mu} E_3\right]} \tag{11}$$

Note that these excitation frunctions differ by factors of -1, $i\omega$, and μ from the excitation functions defined by Ben-Menahem, Rosenman and Harkrider (1970). This is a result of the delta function time history, and source orientation defined in terms of fault plane parameters rather than moment tensor.

APPENDIX 5

SEPARATE SOURCE AND PATH REGIONS

Bache, Rodi and Harkrider (1978), describe a method for synthesizing Rayleigh wave seismograms when the source region structure and propagation path structure differ. In the following expressions the Index 1 refers to the source region, while 2 refers to the propagation path. The vertical component of the Rayleigh wave is given by:

$$\boxed{u = \frac{A_{R1}}{\sqrt{2\pi\omega c_1 a_e \sin\Delta}} X(\theta,h) \left[\frac{c_2}{c_1}\sqrt{\frac{A_{R2}}{A_{R1}}}\right] e^{-\gamma_2 r} e^{\frac{-i\omega r}{c_2}}} \qquad (1)$$

The radial component is given by

$$w = -i\varepsilon_2 u$$

where ε_2 is the ellipticity in region 2.

The excitation functions described in the last appendix can be modified for separate source and travel path structures, by computing them according to Equations (8) through (11) of the last appendix using the source region structure, and then multiplying by

$$\frac{c_2}{c_1}\sqrt{\frac{A_{R2}}{A_{R1}}} .$$

Explicitly, the vertical component of the Rayleigh wave is given by:

$$u = F(N_R, P_R, Q_R, S_R) \times \frac{1}{c_1\sqrt{A_{R1}}} \times c_2\sqrt{A_{R2}} \times \frac{e^{i\frac{\pi}{4}} \times e^{\frac{-i\omega r}{c2}} \times e^{-\gamma_2 r}}{\sqrt{\sin\Delta}}$$

where $\Delta = r/a_e$, with a_e the earth's radius, and F the function defined in Equation 5 of the last section. To generate surface waves from a source described by a moment tensor, the following quantities are needed:

Source region:

N_R, P_R, Q_R, S_R, C_1, A_{R1}

Path region:

C_2, A_{R2}, γ_2, ε_2

In addition, the set of frequencies for each of the above functions must be known, and the distance r and earth's radius must be specified. For the earth's radius, we use $a_e = 6.371 \times 10^6$ m.

APPENDIX 6

INVERSION FOR Q AND MOMENT

The surface wave displacement spectral amplitude is given by:

$$u = M_0 \, S_1(\omega) \, S_2(\omega) \, e^{-\gamma(\omega) r} \tag{1}$$

where M_0 is a constant $= 4\pi\rho\alpha^2\Psi_\infty$ for an explosion, $S_1(\omega)$ depends only on the source structure and $S_2(\omega)$ and $\gamma(\omega)$ depend only on the path structure. Explicitly:

$$S_1(\omega) = \frac{2\beta^2}{\alpha^2}\sqrt{\frac{A_{R1}}{2\pi\omega c_1^3}}\left[\frac{E_3}{2\rho\beta^2} - E_1\right] \tag{2}$$

$$S_2(\omega) = c_2\sqrt{\frac{A_{R2}}{a_e \sin\Delta}} \tag{3}$$

where A_{R1} and A_{R2} are frequency dependent structure excitation functions for source and path regions, c_1 and c_2 are phase velocities for source and path regions, a_e is the earth's radius = 6.371×10^6 M, r is the observation distance and $\Delta = r/a$. E_3 and E_1 are Harkrider eigenfunctions and ρ, α, β are source layer density and velocities.

Note that $S_1(\omega)$ is known for an assumed source region structure, and $S_2(\omega)$ is computed for the inverted structure within the inverse code. In Equation (1) if u is the observed spectrum, then only M_0 and $\gamma(\omega)$ are unknowns. Taking the logarithm of Equation 1,

$$\ell n(u(\omega)) = \ell n(M_0) + \ell n(S_1(\omega)S_2(\omega)) - r\,\gamma(\omega) \tag{4}$$

or:

$$\gamma(\omega) - \frac{\ell n(M_0)}{r} = \frac{1}{r}\;\ell n\;\frac{(S_1(\omega)S_2(\omega))}{u(\omega)} \tag{5}$$

But we also know the relationship between γ and Q (e.g. Mitchell, 1975)

$$\gamma(\omega) = \frac{\omega}{2c^2} \left[\sum_{\ell=1}^{N} \frac{\partial c}{\partial \beta_\ell} \frac{\beta_\ell}{Q_{\beta_\ell}} + \frac{\partial c}{\partial \alpha_\ell} \frac{\alpha_\ell}{Q_{\alpha_\ell}} \right] \tag{6}$$

where ℓ represents a sum over layers in the earth model.

Q_{α_ℓ} is not independent of Q_{β_ℓ}. If bulk losses are small, then

$$\frac{1}{Q_\alpha} = \frac{4}{3}\left(\frac{\beta}{\alpha}\right)^2 \frac{1}{Q_\beta} \tag{7}$$

So we can write

$$\gamma(\omega) = G(\omega,h)\,\frac{\beta(h)}{Q_\beta(h)} \tag{8}$$

where G is the operator defined in Equation (6), or in matrix form:

$$\left[\underset{\approx}{G}(\omega,h),\ -\frac{1}{r} \right] \begin{bmatrix} \frac{\beta}{Q_\beta} \\ \ell n M_o \end{bmatrix} = \frac{1}{r}\,\ell n \left[\frac{S_1(\omega)S_2(\omega)}{u(\omega)} \right] \tag{9}$$

These equations are solved by INVERT. In this way, the Q structure and Moment may be obtained simultaneously. For array data, Equation (8) is solved by INVERT.

APPENDIX 7

PROGRAM TELVEL

This appendix describes in detail the logic of TELVEL and the interactive input/output quantities needed in its execution.

TELVEL

A BRIEF DESCRIPTION OF THE MAIN SUBROUTINES

DEBLIP - Removes blips from input seismograms.

DETRND - Removes the mean and/or linear trend from a given series.

FFTR - Fast Fourier transform.

FIL - Narrow band filter Gaussian filter normalized so that the integral over frequency from minus infinity to infinity is equal to one. Explicitly

$$\mathrm{FIL}(F, FC, Q) = \sqrt{\frac{\alpha}{\pi}}\ \exp\left(-\ \alpha(F-FC)^2\right)$$

where

$$\alpha = \frac{\ln(2)}{2}\left(\frac{Q}{FC}\right)^2$$

FUNRAP - Phase unwraps the phase function in the calling arguments. The user specifies a threshold, defining a 2π discontinuity. Generally the threshold should be between 2 and 3.

GETTS - Retrieves a segment of data from the input device. This version assumes a REALIO file. Segments of length 2**N returned.

GPLOT - Plots group velocity curves from the TPK and APK vectors generated by NBF. GPLOT also plots the "best" group velocity curve as determined by GRPV. The "best" curve will be plotted as a dotted line, the other peaks as integers representing the peak amplitude as a fraction of the largest peak in the plot (in tenths).

GPLOT2 - Plots old and new group velocity curves to enable the user to make the decision as to whether another iteration is necessary.

GRPDLY - Estimates the group delay in a system function by approximating the phase derivative as

$$-\frac{d\phi}{d\omega}$$

The phase derivative is estimated by evaluating the phase of the system function at points on either side of the frequency of interest. If the first differences are equal within a certain tolerance, the phase derivative is computed by taking

$$\frac{\Delta\phi}{\Delta\omega}$$

Otherwise, the step size is decreased and the process repeated.

GRPV - Computes a group travel time-frequency file for a section of a seismogram and plots the dispension curve. With GVFIND, GRPV will also find the "best" dispersion curve.

GVFIND - Picks the dominant group velocity curve from a group travel time-frequency file. To be accepted, a peak must be within a certain time window near the arrival time of a peak in an adjacent frequency band. In addition, the peak must be above a specified amplitude threshold. If several peaks from one filter pass these criteria, then an error "radius" is computed for each peak based on its arrival time and amplitude. The peak with the smallest radius will be accepted.

GVITER - Handles the iterative portion of the velocity determination. GVITER assumes the user will always want to compare results from the previous iteration with the results from the current one before making a decision as to whether another is necessary. Thus, the first step in GVITER is always to compute new group velocity curves from the phase spectrum resulting from the previous iteration. Steps are as follows:

1) in a loop, for each section
   a) get ϕ from the ϕ file
   b) compute $d\phi/d\omega$
   c) compute equivalent group velocity and put answer in temporary arrays

2) ask the user which sections he wants to look at and plot both old and new group velocity curves

3) ask the user if he wants a new iteration:

   a) yes - transfer group velocities from temporary arrays into GV and FV, then exit. The main program will continue with PHAV

   b) no - ask the user if he wants the new or old GV's, then exit and the main program will go to POUT

4) upon return, ITER = 1 if a new iteration was requested. 0 = no.

INTERP - Finds the estimated exact location and amplitude of the peak or trough by fitting a parabola to three adjacent trace points.

LOCPCK - Locates peaks in the filter envelope function. LOCPCK attempts to do the location using the three point rule:

$$X1(I-1) < X1(I)$$
$$X1(I+1) > X1(I)$$

All resulting peak times and amplitudes are saved. The total number of peaks saved is returned in NTOT.

MPLOT - Plots the matched filters generated in PHAV. The Fourier transform of the matched filter is read off the REALIO file, transformed to the time domain and plotted. Only the first LSEC points are plotted so the filters can be compared directly with the seismograms.

NBF - Performs all narrow band filter operations

1) FFT entire time series in place
2) loop over filters and
   a) produce filter output spectrum
   b) produce quadrature spectrum
   c) transform both to time domain
   d) combine these to produce envelope function
   e) calculate the instantaneous phase (optional)
   f) locate the peaks in the envelope function
   g) sort peaks in descending order

PHADE - Computes phase delay curve given the arrival time of peaks in the surface wave train. The method used is to compute approximations to the group arrival time

$$TG = \frac{d\ phase}{d\omega}$$

using the arrival time and the period of the peaks. The derivative is then integrated to give the PHAS array. In addition, frequency - group velocity pairs may be read off an NBF - type dispersion curve.

PHAV - Loops through the sections of the seismogram file and computes a phase delay curve for each section. The method is to integrate the phase derivative as given by the group velocity dispersion curve defined by the vectors GV and FV. PHAV writes out the cross correlations to a second and the phase delay function to a third. The first is given in its frequency domain counterparts since the cross correlating is done in the frequency domain. Each section of these two files contains 2**LOG2N complex numbers corresponding to the FFT of the associated time series.

To perform the cross correlation in the frequency domain, the time series are extended with zeros to length 2**(LOG2N+1), where LOG2N is 1+IFIX($\log_2$ LSEC). The extra zeros are necessary to avoid problems with circular correlation. Consequently, the output time series will be at least twice as long as the length of each section.

POUT - Prints out a summary of the run and the phase and group velocity curves as determined.

PROC - PDP element with a number of useful comments.

PVPLOT - Plots the phase velocities as computed from the phase functions in the file referenced by LUPHI. The user has the option of specifying the section for which to compute the phase velocity and the number of 2π's to add or subtract.

SPLOT - Plots multiple seismograms.

SYSFUN - Evaluates a system function given in terms of a complex polynomial. SYSFUN returns the amplitude and phase of the system function at a specified frequency.

If POLY(1) < 0, the rest of the polynomial will be ignored and the return values will be

AMP = 1.
PHA = 0.

TAPER - Applies a cosine taper to the ends of a given series and returns a tapered series.

TSEDIT - Performs all the time series editing which may include:

1) deblip (remove glitches from data)
2) demean (remove the mean)
3) detrend (remove a linear trend)
4) taper (apply a cosine-bell taper to both ends)
5) insert leading zeros and update start time
6) find the nearest power of 2 for the FFT and pad the time series
7) some processed time series on disc

VELS - The main program

XPLOT - Plot the cross-correlation functions generated in PHAV.

TELVEL

SUBROUTINE	CALLS
FFTC	COOL
FFTR	COOL
GPLOT	GRPDLY
GRPDLY	SYSFUN
GRPV	GETTS, GPLOT, GPLT(GPLOT), GVFIND, NBF, TSEDIT
GVFIND	GRPDLY
GVITER	GPLOT2
LOCPCK	INTERP
MPLOT	FFTR, PHADE
NBF	FFTC, FFTR, FIL (function), LOCPCK
PHADE	GDELAY
PHAV	FFTR, FUNRAP, MPLOT, PHADE, PPLOT(PVPLOT), PVPLOT, SYSFUN, XPLOT
POUT	SYSFUN
TSEDIT	(DEBLIP), DETRND, FFTPRM, TAPER
VELS	GRPV, GVITER, PHAV, PHITER (PHAV), POUT, SPLOT
XPLOT	FFTR

(A) A IS COMMENTED OUT

A(B) A IS AN ENTRY POINT OF B

TELVEL

SUBROUTINE	IS CALLED BY	
COOL	FFTC, FFTR	
DEBLIF	TSEDIT	
DETRND	TSEDIT	
FFTC	NBF	
FFTPRM	TSEDIT	
FFTR	MPLOT, NBF, PHAV, XPLOT	
FIL	NBF	
FUNRAP	PHAV	
GDELAY	PHADE	GDELAY(GRPDLY)
GETTS	GRPV	
GPLOT	GRPV	
GPLOT2	GVITER	
GPLT	GRPV	GPLT(GPLOT)
GRPDLY	GPLOT, GVFIND	
GRPV	VELS	
GVFIND	GRPV	
GVITER	VELS	
INTERP	LOCPCK	
LOCPCK	NBF	
MPLOT	PHAV	
NBF	GRPV	
PHADE	MPLOT, PHAV	
PHAV	VELS	
PHITER	VELS	PHITER(PHAV)
POUT	VELS	
PPLOT	PHAV	PPLOT(PVPLOT)
PVPLOT	PHAV	

SPLOT	VELS
SYSFUN	GRPDLY, PHAV, POUT
TAPER	TSEDIT
TSEDIT	GRPV
VELS	-
XPLOT	PHAV

A(B) A IS AN ENTRY POINT B

TELVEL

SUBROUTINE	HAS THE ENTRY POINTS
GPLOT	GPLT
GRPDLY	GDELAY
GRPV	DONBF
GVITER	TNSFER, TRIGSM
PHAV	PHITER, WINDOW
POUT	TRIAVG
PVPLOT	CONVRT, PPLOT

The following pages are designed to enable the user to execute TELVEL and also be able to locate the section of the code in which control is currently assigned. The format of each prompt is as follows:

```
  ┌number of this prompt
  ▼
  # SUBROUTINE in which prompt is located

    "PROMPT MESSAGE"

         options, comments, etc.
```

1 VELS

"SEISMOGRAM FILE (Q TO QUIT) "

Q - Stop execution

name - Name of REALIO seismogram. Must have constant Δt between points. At end of program, control is restored to this point.

2 VELS

"N SECTS, LEN SECT, DELTA - T, DELAY TIME (+ = LATE) "

B - Go back to 1

N SECT - Number of sections in seismogram.

LEN SECT - Length of this section.

DELTA T - Time interval between data points.

DELAY TIME - Number of seconds between the event time and the start time of the seismogram. A plus value indicates that the seismogram starts after the event time and a negative before.

3 VELS

"DISTANCES (KM), OR NEAREST OFFSET, - INCREMENT "

B - If the first character entered is "B", go back to 2.

distances - There must be at least two distances specified, even though only one section is used. These distances can be input in two ways:

a) - the first value is a distance in km and the second value is a delta distance, also in km. This is indicated by a negative sign preceeding the delta. The sign of the distance (first value) indicates whether the delta is added to (positive) or subtracted from (negative) the starting value. For this case the algorithm is:

DIST(1) = ABS(first value)
DIST(2) = DIST(1) ± increment
DIST(3) = DIST(1) ± 2* increment

b) The actual distances in km are entered. There must be NSEC values and if a "B" is encountered after specification of the second distance, control is transferred back to 3 and the distance input starts over.

4 SPLOT

"SECTIONS TO PLOT - S = ENDLIST, A = ALL, G = GO"

SPLOT plots the seismogram sections requested.

G - Go back without plotting
B - Don't plot. Go back to 3.
A - Plot all the sections
SECTIONS TO PLOT - Each number is taken as a section to be plotted. A letter (eg. "S") will end the list.

If G, B, A or a number have not been entered as the first input, control is transferred to 4 to try again.

5 VELS

"NO. OF FILTERS, F - START, F - END, Q's"

B - Go back to 4.
NO. OF FILTERS - The number of filters to be used between frequency limits specified below.
F START - Starting frequency.
F END - End frequency.
Q - Q of each filter.

The interval (F START - F END) is divided into a number of equally spaced points (the numberof filters) and a filter of width F WIDTH centered at each point.

6 VELS

"SYSTEM FUNCTION FILE (N FOR NONE) "

This is the instrument section.

B - Go back to 5.
N - Do not add instrument
FILE NAME - File name of instrument data. The form is shown below:

A REALIO file of the form:

$P_1 = n$ the degrees of the numerator and
$P_2 = m$ denominator

$P_3 \rightarrow P_{n+3}$ $a_0, a_1, ---, a_n$

$P_{n+4} \rightarrow P_{n+m+4}$ $b_0, b_1, ---, b_m$

where

$$\text{POLYNOMIAL} = \frac{a_0 + a_1x^1 + a_2x^2 + --- + a_nx^n}{b_0 + b_1x^1 + b_2x^2 + --- + b_mx^m}$$

7 GRPV

"SEC # , OPTION (H = HELP) "

If the first input is the letter:

B - Go back to 6.
G - Go on without narrow band filtering, plotting, etc.
H - List all the available options.
S - Set ACUT and TCUT (see 8 for details).
F - Find group velocity curves for the last section processed.
C - For each section, do the narrow band filtering and find the peaks. Then find the group velocity curves.

If the first input is the section number, the options are:

N - Narrow band filter, etc. then plot the group velocity curve.

P - Do a group velocity plot on the data as is.

L - List the velocities for this section number.

E - (Edit) Load in new values for the frequencies and group velocities.

M - (Modify) Use cross hairs to change group velocities.

8 GRPV

"AMP CUT, TIM CUT "

This request is made if "S" has been specified in 7.

AMP CUT - Amplitude cutoff for the group velocity finder section.

TIME CUT - Time cutoff for the group velocity finder section.

9 GRPV

"INDEX, FREQ, GRP V "

This prompt is made if "E" was specified in 7.

This option allows the modification of existing data. Three data must be entered to complete each change, after which the edit made can be terminated by entering any letter.

INDEX - The index of the set to be changed.

FREQ - The frequency.

GRP V - The group velocity.

If "M" is specified in 7, then cross hairs are used. Specify index only. When cross hairs appear, adjust to desired point and press any number to enter. End by setting INDEX = 0.

10 VELS

"ENTER PHASE CORRCTN IN MULTIPLES OF PI (H = HELP)"

B - Go back to 7 and do the GRPV section over.

H - Print the options as a user aid.

PHACOR - (Phase correction; will be multiplied by π) For the case of step explosion, Rayleigh wave, vertical component, up is positive and PHACOR is entered as - 3/4. This value will be multiplied by π.

11 PHAV

"GRP V SECT FOR MATCHED FILTER (A = 1 ON 1) "

B - Go back to 10

A - For each section, the group velocity for the matched filter is that of the section.

GRPV - Input group velocity for the matched filter.

12 PHAV

"MATCHED FILTER BW - (W)HITE, (F)ILTER RANGE "

B - Go back to 11.

W - The frequencies go from zero to the Nyquist frequency.

F - The frequencies go from zero to the highest filter frequency.

BW - The frequencies go from zero to BW.

13 PHITER (ENTRY POINT IN PHAV)

"WINDOW LIMITS (N FOR NONE)?"

B - Go back to 12.
N - No window limits.
WINDOW LIMITS - The lower and upper window limits are read.

14 MPLOT

"SECTIONS TO PLOT - S = ENDLIST, A = ALL, G = GO"

MPLOT plots the matched filter generated in PHAV.

G - Go on without plotting.
A - Plot all sections
SECTIONS TO PLOT - Read sections to plot until an "S" is read.
B - Go back to 13.

15 XPLOT

"SECTIONS TO PLOT - S = ENDLIST, A = ALL, G = GO"

XPLOT plots the cross-correlated matched filter outputs.

G - Go on without plotting.
B - Go back to 14.
A - Plot all sections.
SECTIONS TO PLOT - Read section numbers to plot until an "S" is encountered.

16 PHITER (ENTRY POINT IN PHAV)

"PHASE VEL PLOT - SECT #, N-TWOPI "

B - Go back to 15.
G - Go on without plotting.
any letter - Go back to prompt at 16.
(SECT #, N-TWOPI) where:
SECT # - The section number to be plotted.
N-TWOPI - The number of 2π's to add to the phase.

17 PHITER (ENTRY POINT IN PHAV)

"OPTION (H FOR HELP)"

H - Point out options available.
B - Go back to 15.
P - Loop over - 2π, 0π, 2π, plotting the 0π with a solid line and the others with a dotted line. (PPLOT)
N - Make a new phase velocity plot. (PVPLOT)
G - Go on without plot.
(SECTION NUMBER, NTWOPI) -- This option requires a pair of numbers, the section number and the number of 2π's to add to the phase and increase phase velocity.
L - List the frequencies and phase velocities.

18 GPLOT2

"SECTION #, OPTION (G = GO, N = NEWPLOT)?"

GPLOT2 plots the old and new group velocity curves to see if a new iteration is necessary.

- G - Go on without plotting.
- N - Go back to the start of the subroutine and start a new plot.
- B - Go back to original call to PHAV or PHITER (depending on the iteration number). The first prompt following this transfer is 12.
- L - List the following data:
  index, frequency, old velocity, new velocity.

At this point, if the response to the original prompt was any letter, control is transferred back to the prompt at 18.

SECTION - The section to plot.

At the end of GPLOT2, control is transferred back to the prompt at 18.

19 GVITER

"WANT NEW ITERATION (Y/N) "

- B - Go back just prior to 19 and plot the old and new group velocity curves to see if another iteration is needed.
- N - Go to prompt 20 and set flag so new iteration won't be done.
- Y - Go to 13, flag remains set for new iteration.

20 GVITER

"WANT THE NEW OR OLD GROUP VELOCITES (N/O) "

- B - Go back to 19.

N - Use the new group velocites.
O - Use the old group velocites.
anything else - Go back to 20.

21 POUT

"CLEAR SCREEN FOR RUN SUMMARY"

This is merely a command to clear the screen. No otner action is meaningful.

22 POUT

"SECTION TO PRINT, N - TWOPI (G = GO)?"

B - Go back to call to GVITER. Go back to the original call to PHAV or PHITER (depending on the iteration number). The first prompt following this transfer is 12.
G - Go on without printing.
any other letter - Go to 22 and redo.
(SECTION TO PRINT, N-TWO PI) - Specify the section to point and the number of 2π's to add to the phase.

23 POUT

"START FREQ, END FREQ, AND FREQUENCY INTERVAL?"

B - Go back to 22.
(SF, EF, DF) where

SF = Start frequency.
EF = End frequency.
DF = Frequency interval.

If any letter other than "B" has been entered, go to 23.

24 <u>POUT</u>

"OUTPUT FILE (N = NONE)?"

N - Go back to 22.
B - Go back to 22.
Output file name.

25 <u>POUT</u>

"HEADER LINE?"

Anything entered (up to 80 characters) is used as a header on the output file.

26 <u>POUT</u>

"ENTER L(LOVE) OR R(RAYLEIGH)"

Either an L or R is written on the out put file to identify the type of problem.

Execution for the given seismogram is complete. Go back to 1 and decide whether to start over with a new seismogram or quit.

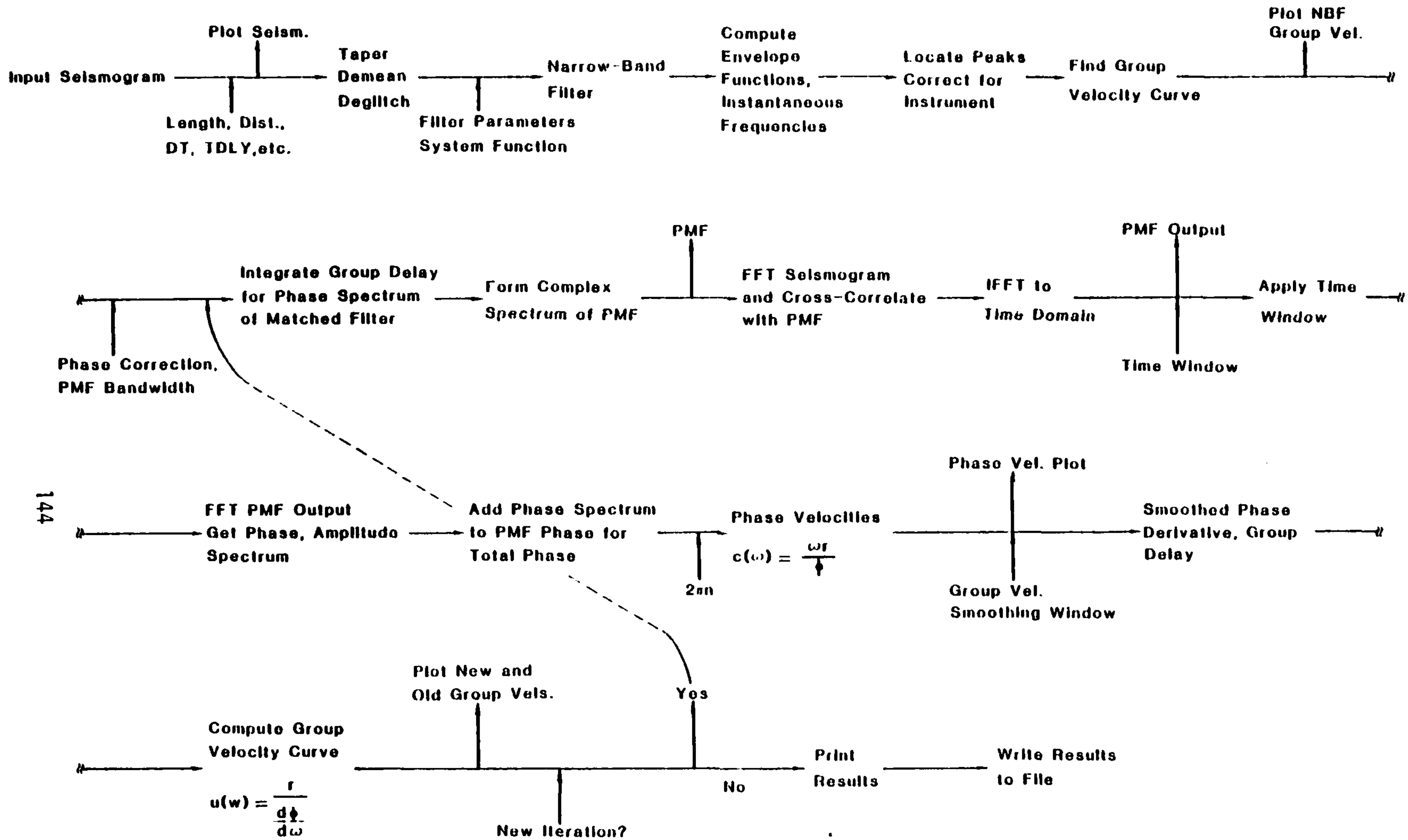
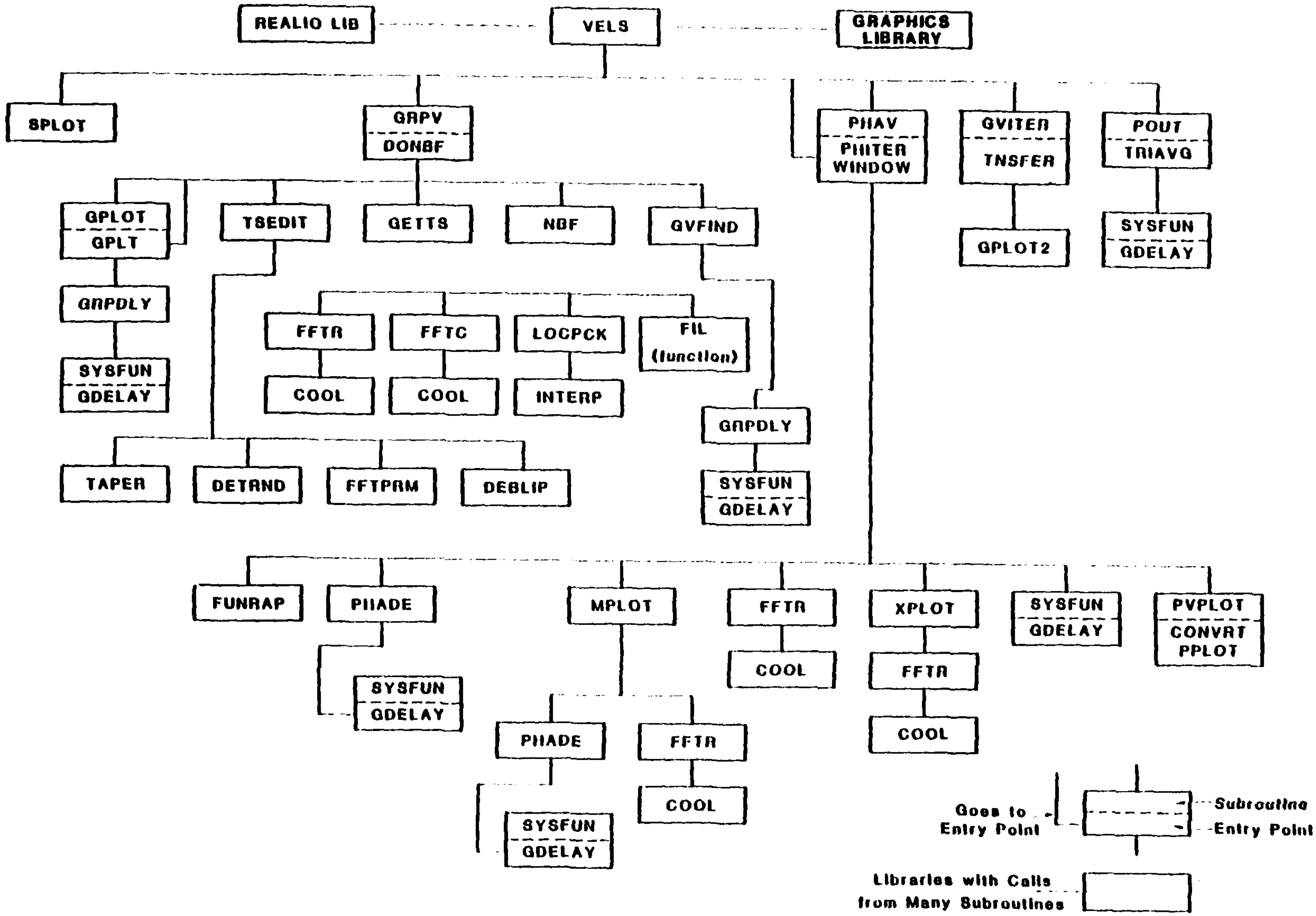


Figure 1. Block diagram, dispersion curve extraction. The program TELVEL uses phase-matched filtering as proposed by Herrin and Goforth (1977).

TELVEL



REALIO LIB
VELS
GRAPHICS LIBRARY
SPLOT
GRPV
DONBF
PHAV
PHITER
WINDOW
GVITER
TNSFER
POUT
TRIAVG
GPLOT
GPLT
TSEDIT
GETTS
NBF
GVFIND
GPLOT2
SYSFUN
GDELAY
GRPDLY
FFTR
FFTC
LOCPCK
FIL
(function)
COOL
INTERP
TAPER
DETRND
FFTPRM
DEBLIP
FUNRAP
PHADE
MPLOT
XPLOT
PVPLOT
CONVRT
PPLOT
Goes to
Entry Point
Subroutine
Entry Point
Libraries with Calls
from Many Subroutines